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Grain legume response to future climate and adaptation strategies in Europe: a review of simulation studies

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Abstract

In Europe, increasing the area of legume crops has been identified as a key measure to achieve the objectives set by the European Green Deal and transition toward more sustainable food systems. Although the role of grain legumes in climate change mitigation has been closely examined, little research has focused on how climate change will challenge the development of these crops. This article systematically reviews recent simulation studies to assess the impact of climate change on grain legume performances in Europe and the effect of adaptation strategies. Forty papers using process-based, ecological niche, or statistical models were selected to simulate the response of eight grain legume species to future climate (2020-2100) in Europe. The lack of data on adaptation strategies in Europe was compensated for by enlarging the study area to climatically similar regions. The review highlights a notable imbalance between research about soybeans versus other grain legumes, with soybeans representing approximately 80% of selected studies. Studies focused on soybeans found good agreement, with yield or suitability gains simulated in Northern Europe and a higher probability of yield losses in Southern and South-Eastern Europe. While a similar spatial pattern may be expected for other grain legumes, the scarcity of data makes this result more uncertain. The review also shows that several adaptation strategies have the potential to mitigate the negative impact of climate change on grain legume performances or enhance its positive impact. The most promising strategies tested include irrigation, change in sowing date, and cultivar choice. In addition, we identify several knowledge gaps that, if addressed, would support legume development in Europe. In particular, key species such as field peas, faba beans, lentils, and chickpeas remain blind spots, despite their prominent role in European environmental, agricultural, and nutritional policies. Other knowledge gaps include a lack of accounting for crop response to elevated CO_2, ozone, and future biotic pressure, and a limited range of adaptation strategies tested and indicators assessed. Implementing multi-criteria analyses that involve stakeholders would help identify relevant input and output for future simulations.

Keywords

Climate change; protein crop; soybean; *Leguminosae*; crop model

1. Introduction

In Europe, increasing the area of legume crops has been identified as a key measure to transition toward more sustainable food systems (Schneider and Huyghe, 2015). Thanks to their ability to fix atmospheric nitrogen (N), legumes contribute to climate change mitigation by reducing greenhouse gas emissions from synthetic fertilizer production and application (Peoples et al., 2019). Legumes are known to provide numerous agronomic services including increased soil N availability benefitting the subsequent crop, improved soil structure, enhanced soil microbial activity, and “break-crop” effect (Jensen et al., 2010; Jensen and Hauggaard-Nielsen, 2003; Köpke and Nemecek, 2010). Legumes grown in rotation can enhance main crop yields, especially in low-input systems (Cernay et al., 2018; Preissel et al., 2015; Zhao et al., 2022). Intercropped with cereals, they allow to increase the total yield in comparison to mean sole crops (Bedoussac et al., 2015). Among all legumes, grain legumes such as soybeans and peas are particularly interesting, as they represent a healthy source of proteins for both animal feed and human food. Substituting grain legumes for animal-based proteins has been proposed as a way to transition toward healthier and more sustainable diets (Davis et al., 2010; Prudhomme et al., 2020; Röös et al., 2020). In this way, increasing the production and consumption of grain legumes is considered a key measure to achieve the objectives set by the European Green Deal and the Farm to Fork Strategy in terms of reducing the environmental footprint of European food systems and ensuring protein self-sufficiency (European Commission, 2020).

In spite of their agronomical, environmental, and nutritional benefits, the production area of grain legumes remains low in Europe. In 2020, they represented less than 4% of European cropland, in contrast to 15.2% worldwide (FAOSTAT, 2023) (Table S1). Numerous interacting factors (e.g. public policies, market dynamics, agronomic R&D activities, and breeding efforts), resulting in a so-called technological lock-in, have hampered their development (Magrini et al., 2016). Yield instability is one component of this lock-in (Watson et al., 2017). Indeed, grain legume yields are often considered to be more variable than cereal yields (Cernay et al., 2015), especially as they are frequently sown in spring, which makes them more exposed to heat stress and water deficit during key stages of their growing cycle (Falconnier et al., 2020; Reckling et al., 2018). Drought (Farooq et al., 2017), cold and heat stresses (Bhat et al., 2022; Gogoi et al., 2018), or waterlogging (Pasley et al., 2020) can strongly affect biological nitrogen fixation (Salon et al., 2011), grain legume growth, reproduction, and yield.

Climate change is likely to increase the occurrence of such stresses, and thus impact grain legume performances (Ahmed et al., 2022; Vadez et al., 2012). Although the role of grain legumes in climate change mitigation has been closely examined (Jensen et al., 2012; Prudhomme et al., 2020), little research has focused on how climate change will challenge their development in Europe. In particular, although a large body of literature has evaluated the effect of a single climatic factor - mainly elevated CO_2, temperature and water stress - on grain legume physiology and performances (Ahmed et al., 2022; Bhattacharya, 2010; Dutta et al., 2022), little is known on how these crops will respond to the simultaneous, climate change-driven variations of all these factors (Hatfield et al., 2011; Rötter et al., 2018; Vadez et al., 2012).

Crop models have been shown to be useful tools for assessing crop responses to climate change, as they can use projections for future climate under different emission scenarios and account for the simultaneous variations in several climate parameters. As several sources of uncertainty are associated with crop models (Wallach and Thorburn, 2017), results may differ among studies. Reviews are therefore needed to synthesize the outcomes of several simulations and assess consensus on the direction of change. To our knowledge, reviews of simulation studies have mainly focused on major crops such as cereals (e.g. Carr et al. 2022; Challinor et al. 2014; Knox et al. 2016). Although some of them include major grain legumes such as soybeans, results often focus on main production areas, for example Brazil, the United States, and Asia in Hasegawa et al. (2022) and Zhao et al. (2017), excluding Europe. However, the impact of climate change on crops is known to vary depending on regions and crop species

(Moore and Lobell, 2015). Therefore, the impact of climate change on grain legumes in Europe needs to be assessed in a crop-specific spatially explicit manner. Recently, several studies have simulated grain legume response to climate change in Europe using different types of models, including process-based crop models (Nendel et al., 2023), machine learning techniques (Guilpart et al., 2022), and ecological niche models (Manners et al., 2020). However, their results may be diverging as in Guilpart et al. (2022) and Manners et al. (2020) for soybeans, which motivates the need for a review.

Adjusting crop management can significantly modify the impact of climate change on crop performances (Abramoff et al., 2023). Here again, crop response to adaptation has been investigated for major crops but less frequently for grain legumes, especially in Europe. We also lack data on the relative potential of different adaptation strategies, as the approach used in existing reviews does not always allow for a comparison of different strategies (e.g. Abramoff et al., 2023; Makowski et al., 2020). As adaptation can take many forms that differ in their intent, spatial scale, timing, actors involved, and effort-to-benefit ratio (Iglesias et al., 2012; Smit and Skinner, 2002), comparing several strategies may help plan an effective adaptation to increase food systems resilience (Rosenzweig and Tubiello, 2007).

Altogether, these points highlight the need to synthesize recent simulation studies to answer the following questions: (i) How will climate change impact grain legume performances in Europe and how will this impact vary across regions and species? (ii) Which adaptation strategies have been assessed and what is their potential to sustain grain legume performances in the context of climate change? To that end, we systematically searched and reviewed the literature on grain legume response to climate change in Europe, with and without considering adaptation.

2. Materials and methods

2.1. Literature search

We conducted a systematic review using the PRISMA guidelines (Page et al., 2021) to select two collections of papers answering each of our research questions (see Figure 1 for the PRISMA flow diagram). We considered articles from peer-reviewed journals, reviews, books, and book chapters published between 01/01/2007 and 01/05/2023. We identified 2865 records from the Web of Science using the following research equation (updated on May 16th, 2023):

TS= (("climat*" AND ("chang*" OR "variabilit*" OR "risk*" OR "smart*" OR "futur*" OR "extrem*" OR "scenario*") OR "global warming*")
AND (“*pea” OR “*peas” OR "Pisum" OR “Cicer” OR “*bean” OR “*beans” OR "Phaseolus" OR "Vigna" OR “faba*” OR “soy*” OR “Glycine max” OR “lentil*” OR “Lens culinaris” OR "lupin*" OR “legum*" OR "proteaginous*" OR "protein crop*")
AND ("model*" OR "simulat*" OR "project*" OR "predict*")
NOT ("Caribbean" OR "fish*" OR "vineyard" OR "grapevine" OR "coffee" OR "cocoa"))

We used generic terms such as “legumes” and “protein crop” but also scientific and common names for the major grain legume species grown in Europe (soybean, pea, bean, faba bean, lentil, chickpea, and lupin). The keywords “Caribbean”, “coffee” and “cacao”, on one hand, and “fish”, “vineyard” and “grapevine”, on the other hand, were excluded because they provided many out-of-scope items containing the terms “bean” and “pea”, respectively. To provide up-to-date information, we excluded articles published before 2007, the year of the IPCC AR4 assessment report.

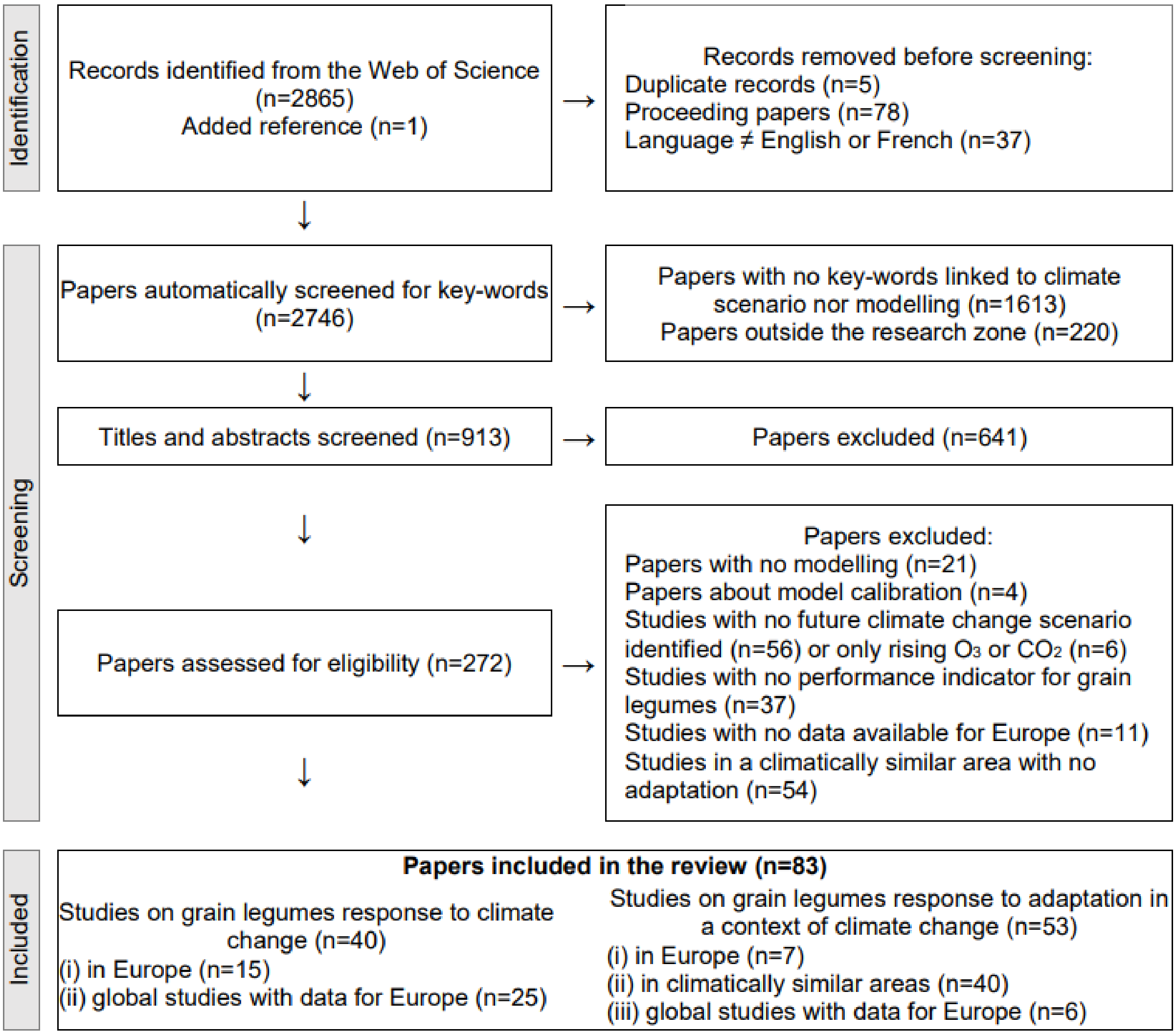

***Figure 1**: PRISMA diagram depicting paper collection and selection. n is the number of papers.*

2.2. Study selection

Two collections of papers were brought together. The “impact” corpus consisted of simulation studies that investigated the impact of climate change on grain legumes in Europe. The “adaptation” corpus was composed of studies assessing how grain legumes respond to adaptation strategies under future climate conditions.

For the “impact” corpus, the study area was limited to Europe, from ca. 35°N to 72°N and 15°W to 40°E, excluding the Russian Federation. For the “adaptation” corpus, results in Europe were too scarce to allow a comparison between several adaptation strategies. Therefore, the study area was enlarged to all regions climatically similar to Europe at the global scale. Climatically similar regions were identified using the Köppen-Geiger climate classification updated by Kottek et al. (2006) and Rubel et al. (2017). The enlarged study area includes regions in Northern America, Southern Brazil, Australia, Iran, Russia, and China (see Section 3.2.1).

To be selected in the "impact" corpus, a publication had to meet the following criteria: (i) study one or several grain legume species; (ii) simulate the impact of future climate change on crop performances using a climate scenario (Free-Air Concentration Enrichment experiments were not considered in this review); (iii) provide data for Europe. Studies conducted at a global scale were selected if it was possible to extract exploitable data for Europe. To facilitate comparison, we considered only climate scenarios from IPCC assessment reports (AR4 to AR6) or the Half a degree Additional warming, Prognosis and Projected Impacts initiative (HAPPI) project. Studies assessing the sole impact of rising O_3 or CO_2 on crop performances were not included.

The indicators used to assess crop performances varied across studies. To facilitate comparison and synthesis, we focused on the main indicators used in selected studies, namely grain yield, crop production, and suitability index. Therefore, in this paper, the term "crop performances" is used to refer to these indicators. Other features of interest such as harvested biomass, water use efficiency, and biological nitrogen fixation (see Section 3.1.1 for the complete list) are referred to as "other indicators"; their response to climate change or adaptation is discussed but not included in figures.

To be selected in the "adaptation" corpus, a publication had to meet the following criteria: (i) study one or several grain legume species; (ii) compare the impact of future climate change on crop performances with and without adaptation; (iii) provide data for Europe or a climatically similar area. Based on Lobell (2014), we defined adaptation as any action undertaken to mitigate negative impacts or enhance positive impacts of climate change on crop performances. We discarded papers in which the nature of the adaptation strategy simulated could not be identified.

After removing duplicates and proceeding papers, a first automated screening was performed with Excel to exclude out-of-scope publications. A list of keywords related to modelling and future climate scenarios was established (Supplementary text 1). When none of these keywords could be found in the title, authors' keywords, or abstract of a record, this record was discarded. Titles and abstracts were also screened for countries and continent names to exclude papers outside the study zone. Then, the titles and abstracts of the 908 remaining papers were assessed manually and 271 articles were selected for full reading. An additional reference (Rosenzweig et al., 2014) was identified from the bibliography of selected papers and added to the "impact" corpus. Finally, 40 papers met all the criteria to be selected in the "impact" corpus, and 53 in the "adaptation" corpus (83 papers in total, with 10 papers belonging to both corpora).

2.3. Data collection

The following data were extracted from the selected papers:

i) crop species under study;

ii) spatial scale of the analysis, defined as site-based studies in which models were run using climate, soil type, and management of one or several particular sites (e.g. Ravasi et al., 2020), studies conducted at regional or country scale using several points or gridded data (e.g. Coleman et al., 2021; Wagner et al., 2016), European or global scale studies (e.g. Nendel et al., 2023; Soares et al., 2021);

iii) temporal scale, i.e. time slices used as "baseline" and "future". When the median point of the future time slice was higher than 2050 it was considered as "far future", otherwise it was considered as "near future";

iv) climate scenario(s) used;

v) model(s) name(s) and type(s), the latter being described using three main categories adapted from Fodor et al. (2017): statistical models that describe the relationship between crop yields and input variables (most often climate variables) in a form of regression or machine learning algorithm, niche models that describe the conditions required for a crop species survival by matching environmental variables with the presence or absence of the crop, and process-based models that use mathematical representations of main biophysical processes driving plant growth, in interaction with environmental and management factors;

vi) abiotic and biotic factors included in the model (e.g. temperature, rainfall, CO_2, pests and diseases);

vii) crop performance indicators assessed.

When available, we collected data for crop performance indicators with and without adaptation in the baseline and the future. The impact of climate change (I_{CC}) and the effect of adaptation (I_a) on crop performances were defined as follows:

$$I_{CC} = \frac{Y_{CC} - Y_0}{Y_0} \times 100 \qquad \text{(Equation 1)}$$

$$I_a = \frac{Y_{CC\_a} - Y_{CC}}{Y_{CC}} \times 100 \qquad \text{(Equation 2)}$$

where Y_0 is the yield (or any other performance indicator) simulated in the baseline period, Y_{CC} is the yield under future climate conditions without adaptation, and Y_{CC_a} is the yield under future climate conditions with adaptation. In the irrigation strategy, the rainfed yield represented the yield “without adaptation”, while the irrigated yield represented the yield “with adaptation”. The effect of switching cultivars was assessed by comparing the highest-yielding cultivar to the other cultivars simulated. When several sowing dates were tested, we selected those that resulted in the highest yield (one or two options) and compared them to sowing dates considered as “standard” in the baseline. For tillage, fertilization or sowing density, the “new” option was compared to the “standard” one. The impact of climate change and the effect of adaptation were evaluated as positive if over +5%, neutral if between -5% and +5%, and negative otherwise.

When results were provided for different locations, time periods, or climate scenarios, the maximum level of detail was kept. When papers did not provide raw data, yields or suitability indexes were extracted from figures using the free software ImageJ (https://ij.imjoy.io/). In the “impact” corpus, when only maps were provided and no aggregated data available, the impact of climate change was appraised using ImageJ and classified into positive, negative, or neutral at a regional or national scale. When models were run at a global scale, only data concerning Europe were extracted. All data were compiled into a .csv file available in the Supplementary materials.

2.4. Data analysis

A spatial representation was chosen to illustrate the impact of climate change on crop performances, highlight regional discrepancies, and identify areas where results diverge between studies. To do so, we counted the number of papers that simulated a positive, neutral, or negative impact of climate change per geographical area, without accounting for the magnitude of change. Some papers provided more details than others (e.g. several combinations of time periods, climate scenarios, and climate models), with results sometimes diverging between the combinations tested. To account for these divergences without giving too much weight to articles testing numerous combinations, an equal weight was given to each article, as in White et al. (2011). For example, if three climate models were considered in a paper, each climate model was given a weight of one third. A regional (NUTS1) scale was found a good compromise between local variability and data availability. When the spatial resolution of simulations was too low, a national scale was used instead. A NUTS3 scale was used to represent site-based studies.

To compare different adaptation strategies, as the level of detail provided in the papers was very heterogeneous, the effect of adaptation was averaged for each paper over all time periods, climate scenarios, climate models, and locations. Several other methods for averaging and aggregating results were tested and conclusions were not found to be sensitive to the method used (Figure S1). It must be noticed that, due to methodological differences and data availability, not all papers mentioned in the corpus description sections could be included in the figures (see Tables S2-3).

Data were analysed and figures elaborated using the free software R version 4.2.2 (https://www.r-project.org/). The R packages mapview (Appelhans et al., 2023), giscoR (Hernangómez, 2023), and magick (Ooms, 2023) were used to create maps, ggplot2 (Wickham, 2016) for figures and kableExtra (Zhu, 2021) for tables.

3. Results

3.1. Impact of climate change on grain legume performances without adaptation

3.1.1. Description of selected studies

Forty studies simulated the impact of climate change without adaptation on one or several grain legumes in Europe. A large majority of them (80%) focused on soybeans, followed by peas and beans (13% each) (Table 1). Only 45% of selected papers differentiated between rainfed and irrigated conditions, while 35% considered a combination of both, and 20% failed to specify the irrigation status.

Global scale studies were largely predominant (63% of papers) (Table 2a). The others were almost equally distributed between European scale (10%), national or regional scale (15%), and site-based studies (13%). Process-based models were more common (55%) than niche models (25%) and statistical models (20%) (Table 2b). Future time horizons differed between species (Figure 2a): for soybeans, a majority of studies focused on the far future, with two peaks around 2050 and 2100, whereas for other pulses, the impact of climate change was mainly assessed for the near future (before 2050). 55% of selected papers compared two or more climate scenarios. RCP4.5 (moderate warming) and RCP8.5 (intense warming) were the most studied scenarios, with 55% of selected papers using at least one of them (Table 2c).

Only a small number of papers considered crop response to elevated CO_2 (45% of the corpus) or ozone (8%). Only five papers (13%) were found on the combined impact of climate change and weeds or pests. Although the three soybean pests (the soybean stem fly *M. sojae*, the southern armyworm *S. eridania,* and the red-banded stink bug *P. guildinii*) and two bean pests studied (the Asian soybean rust *P. pachyrhizi* and the beet armyworm *S. exigua)* were not currently of major concern in Europe, they could become an issue if they were to expand beyond their native range.

The impact of climate change was measured on grain yield in 63% of select studies (36% of them providing absolute grain yield data and 64% relative changes) and on suitability index in 25% of cases (Table 2e). Only 4 papers (10%) analysed yield variability and risks of crop failure. About 10% and 15% of studies investigated the impact of climate change on crops' water use efficiency and water demand, respectively, while only one paper focused on biological nitrogen fixation (Table 2f). Economic indicators were seldom used to study the future profitability of grain legumes (1 paper).

Table 1: *Number of papers in the "impact" and "adaptation" corpus, per crop species and irrigation use*

	Soybean	**Bean**	**Pea**	**Faba bean**	**Chick-pea**	**Cow pea**	**Lentil**	**Lupin**	**Total***
"Impact" corpus	32	5	5	2	1	1	1	1	40
of which:									
rainfed crops	*11*	*4*	*2*	*1*	*1*	*1*	*1*	*1*	*16*
irrigated crops	*4*	*1*	*1*	*0*	*0*	*0*	*0*	*0*	*6*
composite (mix of rainfed and irrigated crops)	*14*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*14*
unclear	*7*	*0*	*2*	*1*	*0*	*0*	*0*	*0*	*8*
"Adaptation" corpus	41	2	5	1	4	0	0	1	53

* A paper can appear in several categories.

Table 2: *Description of selected studies simulating grain legume response to climate change ("impact" corpus) and adaptation ("adaptation" corpus). We present here the number of papers per spatial scale of the analysis (a), type of model used (b), climate change scenario (c), biotic and abiotic parameters considered (d), and indicators assessed (e-f).*

	Impact			**Adaptation**		
a) Spatial scale of the analysis	**Soybean**	**Other grain leg.**	**Total***	**Soybean**	**Other grain leg.**	**Total**
Global scale with data for Europe	23	2	**25**	6	0	**6**
European scale	4	1	**4**	1	0	**1**
Country scale	3	1	**4**	2	0	**2**
Regional scale	0	2	**2**	20	6	**26**
Site-based studies	2	3	**5**	12	6	**18**

b) Type of model*						
Process-based model	18	4	**22**	37	11	**48**
Niche model	8	3	**10**	0	0	**0**
Statistical model	7	1	**8**	4	1	**5**
Others[a]	1	1	**2**	0	0	**0**
c) Climate change scenario used*						
SRES scenarios (IPCC AR4)						
A1B	7	4	**11**	14	3	**17**
A2	5	3	**8**	8	2	**10**
B1	1	1	**2**	4	0	**4**
RCP scenarios (IPCC AR5) & SSP scenarios (IPCC AR6)						
RCP2.6 / SSP1-2.6	4	0	**4**	5	0	**5**
RCP4.5 / SSP2-4.5	13	4	**16**	20	7	**27**
RCP6.0	3	0	**3**	2	0	**2**
SSP3-7.0	0	0	**0**	2	0	**2**
RCP8.5 / SSP5-8.5	18	3	**21**	21	7	**28**
HAPPI scenarios						
+1.5°C World	2	0	**2**	0	0	**0**
+2°C World	1	0	**1**	0	0	**0**
d) Climate parameter and biotic stresses considered*						
Temperature	32	9	**40**	41	12	**53**
Rainfall	30	8	**37**	41	12	**53**
CO_2	15	3	**18**	24	9	**33**
Biotic stress (pest, weed, pathogen)	4	1	**5**	0	1	**1**
Ozone	3	0	**3**	0	0	**0**
e) Crop performance indicators assessed*						
Grain yield (relative changes in %)	14	2	**16**	13	5	**18**
Grain yield (absolute values in t/ha)	6	3	**9**	24	6	**30**
Suitability index	8	3	**10**	2	0	**2**
Yield variability or risk of crop failure	3	1	**4**	1	1	**2**
Crop production	2	0	**2**	3	0	**3**
f) Other indicators assessed*						
Irrigation demand	3	3	**6**	4	3	**7**
Risk of pest occurrence	4	1	**5**	0	1	**1**
Water use efficiency	3	1	**4**	5	5	**10**
Biomass or biological N fixation	0	1	**1**	4	1	**5**
Economic indicators	1	0	**1**	1	1	**2**
Future water availability	0	1	**1**	1	1	**2**
Soil organic carbon, nutrient balance or erosion	0	0	**0**	8	1	**9**
Greenhouse gas emissions	0	0	**0**	3	1	**4**
Yield loss due to pest	0	0	**0**	0	1	**1**
Others[b]	2	1	**3**	1	0	**1**
g) Total						
	32	**9**	**40**	**41**	**12**	**53**

* A paper can appear in several categories.

[a] Includes: agroclimatic indicators (1), probabilistic model (1)

[b] Includes: agroclimatic indicators (1), probability of maturing (1), risk for non-existing adapted varieties (1), time of emergence (1)

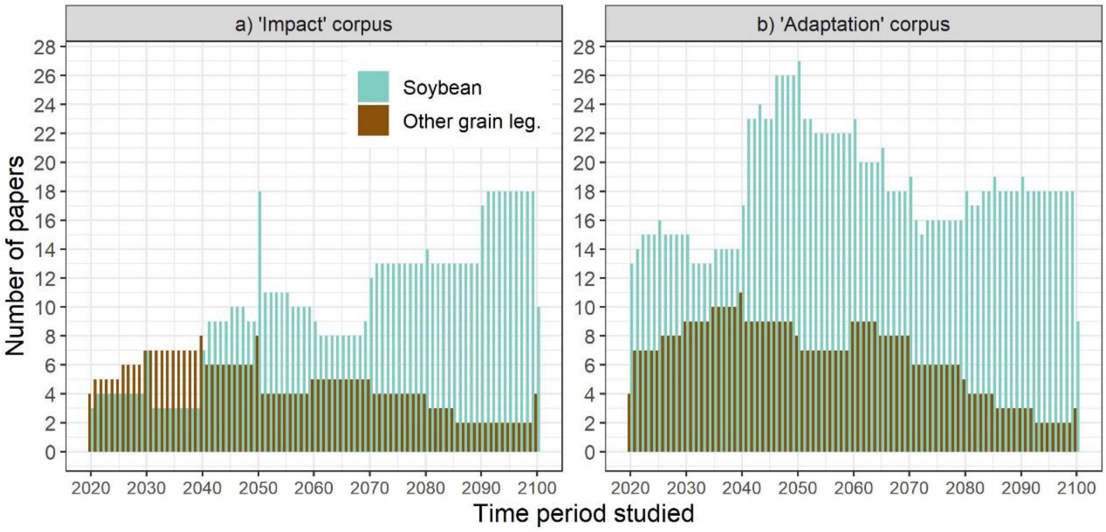

***Figure 2:** Number of papers in the "impact" (a) and the "adaptation" corpus (b) per future time period studied*

3.1.2. Impact of climate change on soybean performances without adaptation

For soybeans, although papers selected in the "impact" corpus covered the whole European continent (Figure 3), more data were available for current production hotspots (11 to 14 papers in Southern France, Northern Italy, and South-Eastern Europe) than Northern Europe (7 to 8 papers in the Baltic states and Scandinavia). Two reasons may explain this discrepancy: site-based studies were more numerous in countries where soybeans are currently grown (Figure S2), and global-scale simulations did not always consider high latitudes.

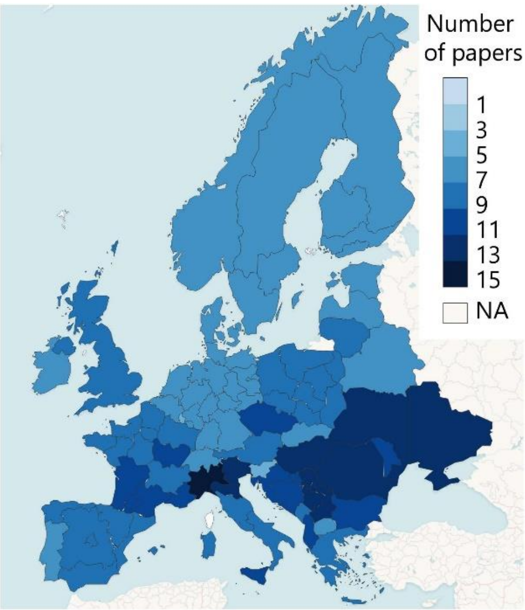

Figure 3: *Number of papers simulating the impact of climate change on soybean performances without adaptation per geographical area. Due to methodological differences and data availability, only 21 papers of the "impact" corpus were included here (see Table S2).*

The impact of climate change was found to vary spatially, with yield gains simulated in the North and a higher probability of yield losses in the South (Figure 4). All studies simulated a neutral or positive impact of climate change on soybean performances in the British Isles, Germany, Austria, Czech Republic, Western Poland, Belarus, and the Baltic states (Coleman et al., 2021; Feng et al., 2021; Guilpart et al., 2022; Manners et al., 2020; Rosenzweig et al., 2014; Soares et al., 2021; Tatsumi et al., 2011). Yield gains were simulated in the South of Finland and Sweden, but not in Norway.

Conversely, a negative impact of climate change was simulated in Northern Italy and South-Western France (Deryng et al., 2014; Guilpart et al., 2022; Jägermeyr et al., 2021; Lesk et al., 2021; Osborne et al., 2013; Tatsumi et al., 2011), with up to 60% of agreement among studies on the sign of change. In Eastern Europe, results were more diverging. Irrigated soybeans were found to benefit from rising temperatures in Serbia (Jancic et al., 2015; Mihailović et al., 2015; Tovjanin et al., 2019) and Croatia (Marković et al., 2020). Deryng et al. (2014) also found an overall positive impact in Eastern Europe under RCP8.5. Conversely, yield losses were simulated in several studies (Deryng et al., 2011; Guilpart et al., 2022; Jägermeyr et al., 2021;

Lesk et al., 2021; Ruane et al., 2018; Tatsumi et al., 2011). Consensus among studies was low in this area, with less than 40% agreement on the sign of change (Figure 4).

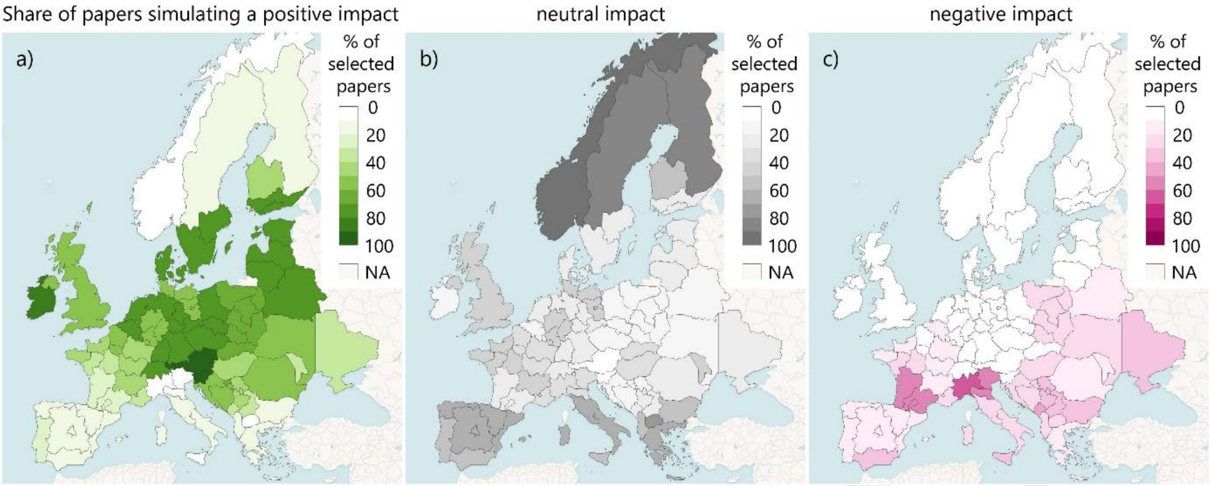

Figure 4: *Share of papers simulating a positive (a), neutral (b), and negative (c) impact of climate change on soybean performances. The share is calculated by dividing the number of articles simulating a positive (resp. neutral and positive) impact by the total amount of articles for each geographical area. Articles are weighted as explained in the Materials and methods section (one article testing two climate models with positive results for one and negative results for the other will be counted as 0.5 positive and 0.5 negative).*

Except for Ukraine, the impact of climate change was more contrasted in the far future (Figure 5d-f) than near future (Figure 5a-c), with a decrease in the proportion of “neutral” results and an increase in the proportion of “negative” and “positive” results. Unsurprisingly, results were slightly more contrasted for warmer scenarios (RCP6.0 and RCP8.5) than others (Figures S4-5). Niche models seemed slightly more conservative than process-based models, with a higher proportion of “neutral” results, while statistical models were more contrasted (Figures S6-7). This discrepancy may arise from differences in model structure or from the methodology used in data collection. Simulations considering CO_2 were usually more optimistic than those without CO_2 (Figures S8-9). However, even when the effect of CO_2 was accounted for, the impact of climate change remained negative in some simulations for Serbia, Bosnia, Hungary (Jägermeyr et al., 2021), Italy (Osborne et al., 2013) and Southern France (Deryng et al., 2014).

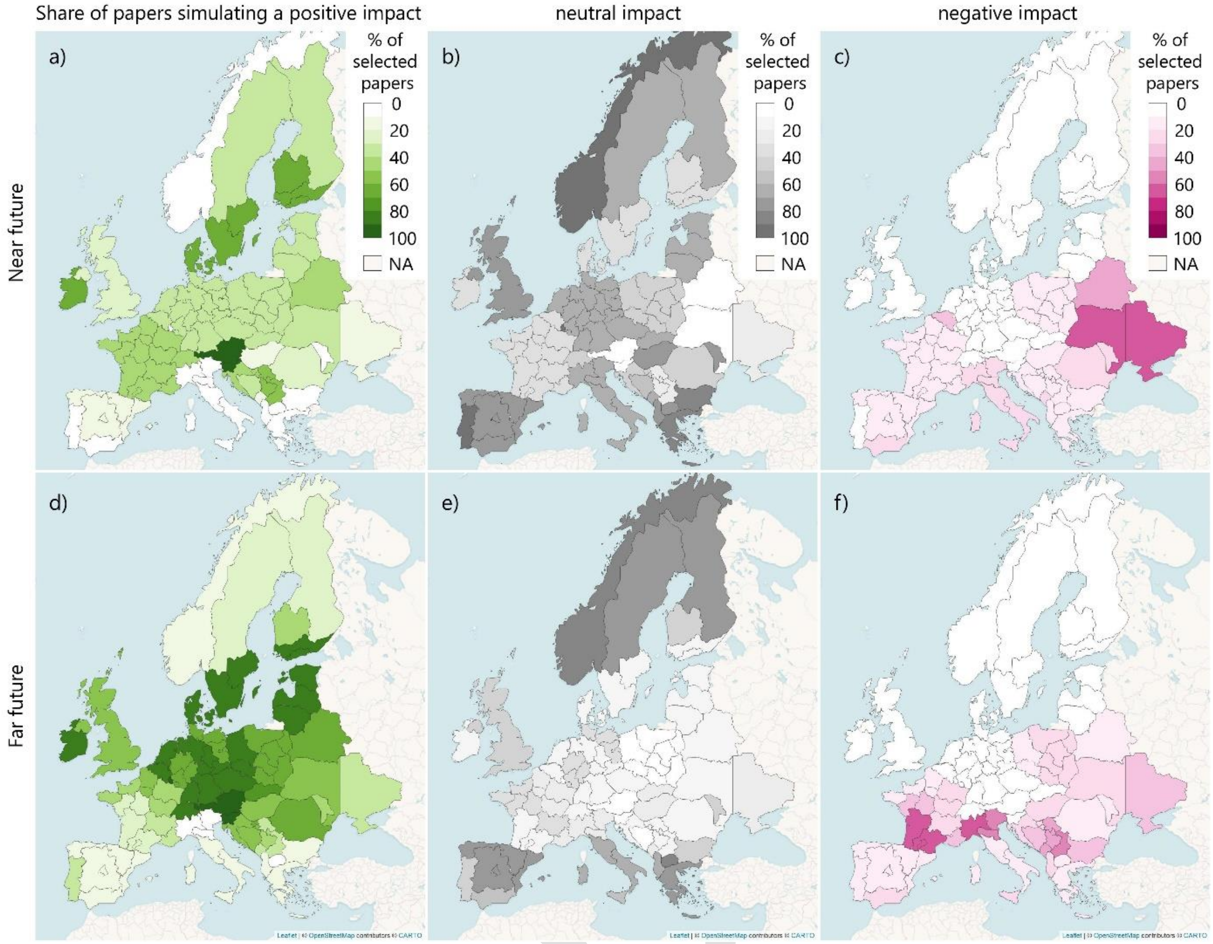

Figure 5: *Share of papers simulating a positive (a, d), neutral (b, e), and negative (c, f) impact of climate change on soybean performances in the near (≤2050) (a-c) and far future (>2050) (d-f). Figure S3 shows the number of articles for each geographical area.*

Additional damages from ozone exposure were simulated by Tai et al. (2014) and Tai and Val Martin (2017), whereas soybeans were almost unaffected by this factor in Lombardozzi et al. (2018). In addition to these abiotic factors, an increased pressure from some weeds and insect pests was simulated. The risk of parasitism increased for three of the five *Cuscuta* species studied by Cai et al. (2022). Future climate conditions in Europe were also found favourable for the expansion of *P. guildinii* and *M. sojae* (Chen et al., 2023; Marchioro and Krechemer, 2023), whereas *S. eridania* was not identified as a serious threat for soybeans (Weinberg et al., 2022).

3.1.3. Impact of climate change on other grain legume performances without adaptation

Very few studies were found on other grain legumes (9 papers, Table 1), so robust spatial patterns of climate change impact could not be identified for these crops. Despite this, the few studies available still offer some useful insights, which are outlined below. The most complete was the work of Manners et al. (2020), who studied the impact of climate change in 27 European countries on 13 legumes and pseudo-cereal protein crops (only 8 grain legume species were retained in our analysis). The simulated spatial pattern was similar to that found for soybeans (see Section 0.), with a positive impact of climate change for almost all crops in the British Isles and Northern Europe in 2050, and suitability losses in Southern Europe, especially in France, Portugal, and Hungary. Andean lupin was found to benefit the most from future climate conditions, whereas blue lupin benefitted the less.

In agreement with Manners et al., Ramirez-Cabral et al. (2016) found an increased suitability for beans in Northern Europe under climate change. In Eastern Europe, France, and the Mediterranean area, results were more uncertain, as suitability strongly decreased with one climate model and increased with the other. In Greece, climatic conditions became less favourable for bean growth (van der Schriek et al., 2020), while only a negligible impact was found in Germany in the near future (Wagner et al., 2016). In Western and Northern Europe, the risk of damage from *P. pachyrhizi* and *S. exigua* was expected to rise from low to medium levels for this crop (Ramirez-Cabral et al., 2019).

Spring pea yields responded positively to rising temperatures in Finland (Peltonen-Sainio et al., 2009). Conversely, a productivity loss due to increased drought and heat stress was simulated in France and Italy (Falconnier et al., 2020; Ravasi et al., 2020).

3.2. Effect of adaptation strategies on grain legume performances

3.2.1. Description of selected studies

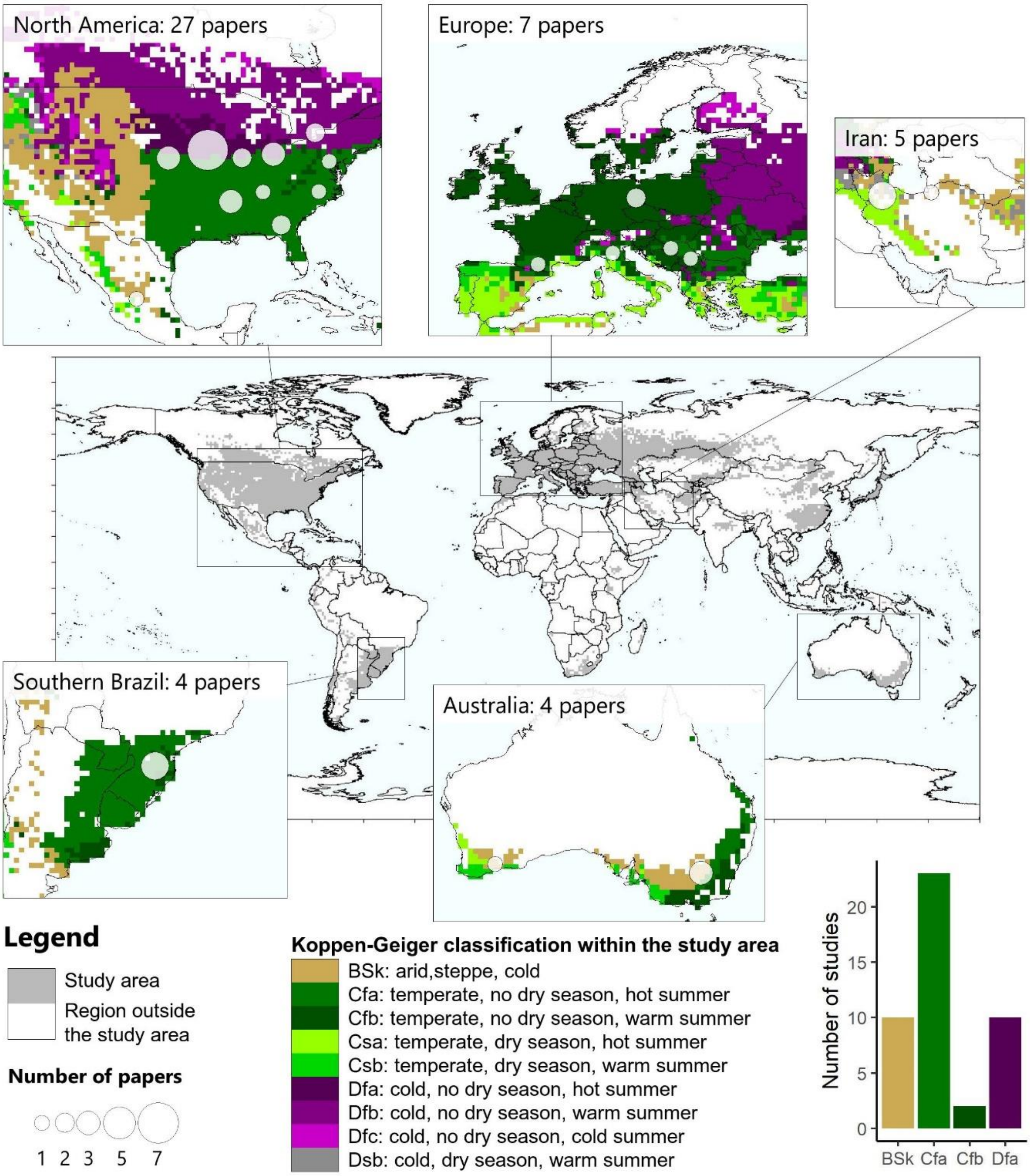

Figure 6: *Study area and geographical distribution of the papers selected in the "adaptation" corpus. The study area is composed of Europe and climatically similar regions. We used the Köppen-Geiger climate classification updated by Kottek et al., (2006) and the script provided by Rubel et al., (2017) to build the maps.*

Fifty-three papers assessed the effect of adaptation on grain legume performances. Among them, only 13% were located in Europe, and 11% were global studies providing data for Europe (Table 2a). The remaining 76% were located in climatically similar regions and were divided between Northern America (51%), Southern Brazil (8%), Iran (9%), and Australia (8%) (Figure 6). Soybeans were studied in 77% of papers, followed by peas (9%) and chickpeas (8%) (Table 1). Only process-based and statistical models were used for these simulations (Table 2b).

Unlike the “impact” corpus, the first part of the century was more studied than the far future, both for soybeans and other grain legumes (Figure 2b). RCP4.5 and RCP8.5 remained the most studied climate scenarios, used in 60% of papers (Table 2c). All studies accounted for changes in temperature and rainfall, and 62% of them considered the effect of CO_2 (Table 2d). Only one paper accounted for biotic stresses, and none of the selected studies considered the effect of ozone.

The effect of adaptation was measured on grain yield in 91% of papers, with 62% of them providing absolute grain yield data and 38% relative changes (Table 2e). Similar to the “impact” corpus, studies assessing the effect of adaptation on yield variability were scarce (2 papers). Numerous studies investigated the effect of irrigation, which explains the higher number of results on crop water use efficiency (19%), future water demand (13%), and water availability (4%) (Table 2f). Some variables assessed in the “adaptation” corpus were not considered in the “impact” corpus, for example greenhouse gas emissions (8%), soil organic matter content, or soil erosion (17%). This suggests that adaptation strategies are also often assessed for their contribution to climate change mitigation. Economic indicators remained scarce (2 papers).

Crop management options were studied in 53% of papers, and soil and water management in 62% (Figure 7). Irrigation was the most studied technical option (40%), followed by modified sowing dates (23%), cultivar choice (19%), and virtual genotype (13%). Combinations of several adaptation strategies were seldom assessed (26% of selected studies), and little variety was found in the choice of the strategies combined (changes in sowing date and cultivar choice represented 64% of the combinations tested). Results on the effect of adaptation mostly apply to soybeans, as few data were available for other grain legumes. Faba beans and lupins represent extreme cases, with only one paper found for each species.

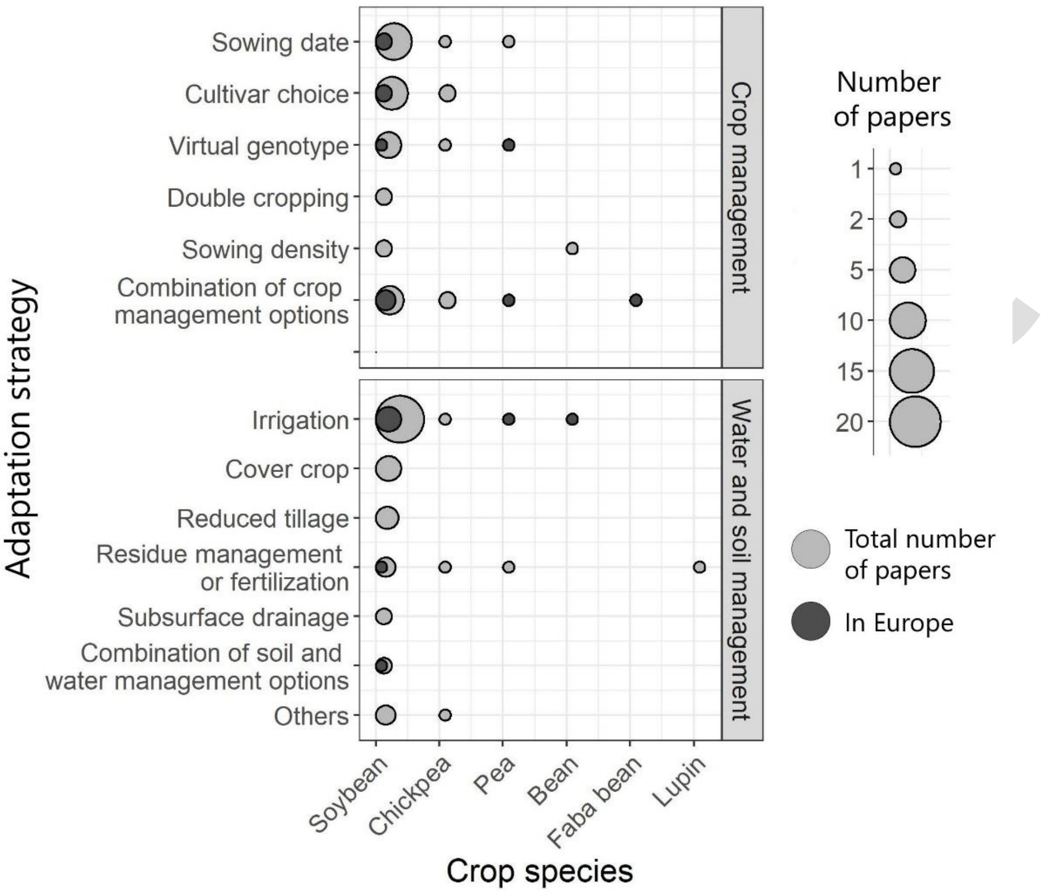

Figure 7: *Number of papers per crop species and adaptation strategy. The size of the circle is proportional to the number of papers. Light grey circles represent the total number of papers and dark grey circles the number of studies focusing on Europe. A same paper can appear in several categories.*

3.2.2. Crop management

The effect of shifting cultivar and sowing date was assessed on soybean performances in a majority of cases (76% of papers), but data were also available for peas (12%) and chickpeas (12%) (Figure 7). The simulated effect was neutral or positive in all studies, but its magnitude varied significantly among locations and species (from 4% to more than 100% yield increase) (Figure 8). Combining cultivar choice and changes in sowing date appeared as the most efficient strategy, with yield gains higher than 20%. Benefits were simulated not only on mean yield but also on yield stability (Falconnier et al., 2020) and pest management (Salam et al., 2011). In most studies, the choice of the optimal maturity group, cultivar, and sowing date was site-specific (Bao et al., 2015a; Nendel et al., 2023; van Versendaal et al., 2023). For example, in Canada (Jing et al., 2017) and in South-eastern Europe (Minoli et al., 2022), early-sown soybeans benefitted from a longer growing season and higher yields, while in the USA, late sowing was identified as an adaptation strategy to avoid heat and water stress occurring earlier in the growing season (Bao et al., 2015b, 2015a).

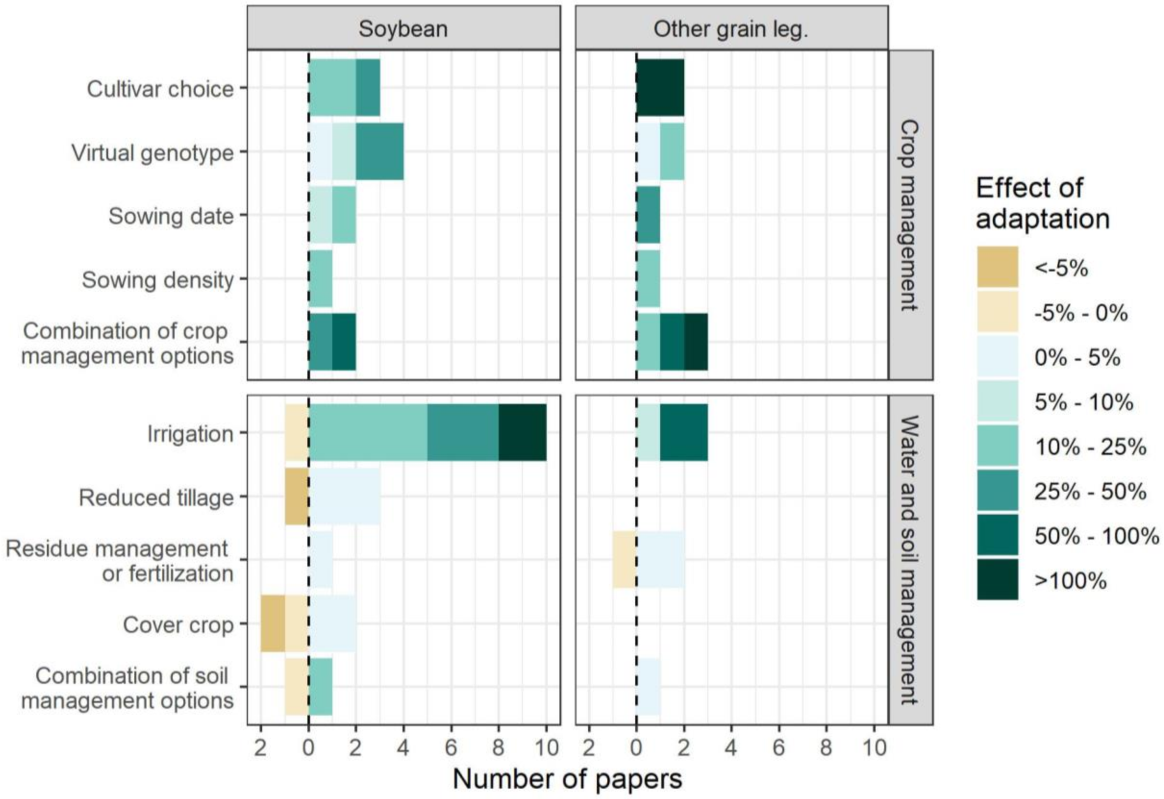

Figure 8: *Effect of different adaptation strategies on crop yields for soybeans (left) and other grain legumes (right). For each paper, the effect of adaptation is calculated as the ratio of the yield with adaptation to the yield without adaptation (expressed in %) and averaged over all time periods, climate scenarios, climate models and locations considered in that same paper (see Methods for details). Due to methodological differences and data availability, only 34 papers of the "adaptation" corpus were included here (see Table S3).*

When designing virtual genotypes, the crop cycle length was often studied as a key parameter to maintain or increase yields under climate change (Fu et al., 2016; Jing et al., 2017; Minoli et al., 2022; Osborne et al., 2013; Ravasi et al., 2020; Soltani and Sinclair, 2012). In several studies, extending the length of the growing period, and especially the grain filling period (Fu et al., 2016), was found to offset the negative impact of elevated temperature on crop cycle duration and soybean yields (Jing et al., 2017; Minoli et al., 2022). Conversely, in some areas where water and thermal stresses were frequent (e.g. Southern France), an early maturity was found preferable for this crop (Minoli et al., 2022). A reduced vegetative phase allowing an early flowering also gave positive results for peas in Italy (Ravasi et al., 2020) and chickpeas in Iran (Soltani and Sinclair, 2012). Other crop parameters were also explored, such as maintaining the harvest index to current levels for soybeans (Jing et al., 2017) and widening the optimal temperature range for peas (Ravasi et al., 2020). Increased drought resistance was obtained for soybeans by manipulating water-related traits (rooting depth, transpiration function) (Battisti et al., 2017) or irradiating seeds with gamma rays (Beiranvand and Ghamghami, 2022).

Other crop management options tested included double-cropping and changes in sowing density. In the USA, climate change alleviated phenological constraints and allowed for expanding winter wheat-soybean double-cropping (Seifert and Lobell, 2015), especially in areas where the suitability of a corn-soybean rotation was predicted to decline (Lant et al., 2016). Sowing density influences within-crop competition for light, nutrients, and water, and was tested as an adaptation strategy for beans in Mexico (Baez-Gonzalez et al., 2020) and for soybeans in Brazil (Battisti et al., 2018). Increasing crop density led to higher yields due to faster leaf area development (resulting in better radiation interception) and reduced soil evaporation (Battisti et al., 2018). For beans, however, increasing sowing density also led to a higher occurrence of water stress (Baez-Gonzalez et al., 2020).

3.2.3. Irrigation

A positive effect of irrigation was found in a majority of cases (92%), with yield increases ranging from 8% to more than 100% (Figure 8). In Germany, both bean (Wagner et al., 2016) and pea yields (Nendel et al., 2014) have been shown to increase with irrigation. Yield gains were also simulated for soybeans in Eastern Europe (Elliott et al., 2014; Marković et al., 2020; Mihailović et al., 2015), in Iran (Araji et al., 2018), in the USA (Bao et al., 2015b; Ma et al., 2021; Timilsina et al., 2023; Zhu et al., 2019) and in Southern Brazil (Battisti et al., 2018). Conversely, in the USA, Lychuk et al. (2017) and Paul et al. (2020) found a non-significant or negative impact of irrigation on soybean yields in the long term, possibly due to higher nutrient leaching under irrigated conditions. Irrigation was found to reduce yield instability for American soybeans by Zhu et al. (2019).

Although irrigation seemed effective to adapt to climate change, strong hypotheses were often made in simulations that did not always reflect the reality experienced by farmers. In particular, irrigation water availability was often considered infinite, whereas huge challenges already exist today in water availability. Future water availability was assessed in only two papers, with diverging results. In Germany, Wagner et al. (2016) estimated that only 33% to 43% of the studied area could provide all the water required for pea irrigation under future climate conditions. On the opposite, Elliott et al. (2014) estimated that renewable water available for irrigation would still exceed demand in most European countries. Optimizing irrigation systems may be required to make the most of the available water resources. For example, Amiri et al. (2021) pointed out the importance of irrigation timing and found that chickpeas benefitted more from supplemental irrigation at the pod-filling stage than at the flowering stage. Another optimization simulated by Baule et al. (2017) was the use of sub-irrigation, i.e. water capture and recycling for summer irrigation.

3.2.4. Soil management

Soil management options were presented as interesting strategies for both adaptation and mitigation, in order to design “climate-smart” systems. Climate change is indeed expected to affect N processes (enhanced mineralization, reduced biological nitrogen fixation), and thus indirectly impact crop performances (Elli et al., 2022; Malone et al., 2020). Management options such as reduced tillage, crop residue incorporation, and cover crops, which play a role in N processes, were assessed both for the environmental services they could provide and for their potential to sustain crop performances in the context of climate change.

Switching to conservation tillage or implementing a cover crop during the previous winter was only tested for soybeans (Figure 7). These two management options were found to have a positive impact on water storage (Li et al., 2021), soil erosion, and nutrient leaching (Panagopoulos et al., 2014). The effect of reduced tillage on crop performances was found neutral (He et al., 2018; Panagopoulos et al., 2014, 2015; Parajuli et al., 2016), except in He et al. (2018) where no tillage reduced yields under severe climate change. Likewise, implementing a rye or a wheat cover crop in winter had no significant effect in Li et al. (2021), Malone et al. (2020), and Panagopoulos et al. (2015). A slight yield reduction was observed in Basche et al. (2016) and Panagopoulos et al. (2014), especially for dry years, and was attributed to the competition between soybeans and cover crops for nutrients and soil water. As they provided environmental services without significantly harming crop yields, these options were advocated as mitigation and adaptation strategies (Malone et al., 2020).

Crop residue incorporation was assessed in several papers in Australia to reduce soil erosion and improve water and organic matter content. Neither chickpeas (Liu et al., 2017) nor lupins (Wang et al., 2019) nor peas (He et al., 2022) did respond to residue management. Adapting fertilization to increase crop yields under climate change was not found efficient either (Lychuk et al., 2017; Wang et al., 2019).

4. Discussion

4.1. The impact of climate change on future grain legume production remains uncertain in Europe

Conclusions on the impact of climate change mostly apply to soybeans, as very few data were available for the other crops. For soybeans, we found a good agreement between studies, with yield gains simulated in Northern Europe and a higher probability of yield losses in Southern and South-Eastern Europe. This spatial pattern of climate change impact is consistent with expectations from climate projections and crop physiology knowledge. Indeed, while climate change is expected to lengthen crop growing seasons in the North, it may lead to faster crop development in the South and increase the occurrence of stresses, eventually causing yield losses (Osborne et al., 2013). A similar spatial pattern was found for wheat, another C3 crop, by Hristov et al. (2020).

These conclusions were relatively robust across climate scenarios, time periods, and types of models. In some regions, the divergences between studies may be explained by differences in model inputs (e.g. climate models and scenarios), structure, or parameters (Wallach and Thorburn, 2017). Additional work is needed to quantify these sources of uncertainty, as it has been made for major crops (Li et al., 2015; Rosenzweig et al., 2014). In particular, a major source of uncertainty arises from models often neglecting the impact of CO_2 (considered in only 36% of selected papers), ozone (4%), and abiotic stresses such as cold snap and waterlogging (not assessed in this review).

Our analysis did not make it possible to assess whether yield gains in the North will compensate for yield losses in current soybean production hotspots, mainly located in Southern and Eastern Europe (Figure S2). Indeed, the few results available were diverging. While Guilpart et al. (2022) simulated a reduction of high-yielding production areas under climate change, resulting in a decrease in the average soybean yield in Europe, Nendel et al.

(2023) found an overall productivity gain. To assess how climate change will impact the average grain legume yield and production at the European scale and identify future production hotspots, we suggest that future simulations should provide absolute yield values instead of relative values. Indeed, relative changes can easily reach very high values when the baseline yield is low. Therefore, even with a strong positive impact of climate change in Northern Europe, future soybean yields in these areas may not be attractive to farmers.

4.2. Adaptation strategies can mitigate the impact of climate change on grain legumes

This review showed that adaptation strategies have the potential to mitigate the negative impacts of climate change or enhance its positive impacts. Yet, the strategies investigated differed in their effects on yields. Overall, irrigation and crop management options resulted in significant yield gains. A neutral or slightly negative effect on yields was frequently simulated for alternative soil management and fertilization, which was not surprising given grain legume reliance on biological nitrogen fixation (Liu et al., 2017). However, these options provided secondary benefits, for example soil erosion prevention, which could motivate their adoption.

Our analysis revealed an imbalance between relatively well-studied strategies (e.g. irrigation or change in sowing dates) and strategies whose potential remains to be examined (e.g. intercropping). Combining different adaptation strategies also appears as a promising yet underexplored strategy. In particular, we suggest water-saving soil management options should be tested in combination with optimized irrigation systems, in order to sustain yields in spite of a growing pressure on water resources. Engaging stakeholders in the co-design of adaptation strategies would help identify relevant combinations and increase the scope of strategies tested (Farrell et al., 2023; Tui et al., 2021).

Our assessment of the adaptation effect involves some limitations both from the method used in the review and in selected papers. First, our work does not consider the dynamic evolution of adaptation efficiency. In particular, Lobell (2014) distinguishes between an “impact-neutral” adaptation strategy (e.g. a strategy enhancing yields by 10% both in baseline and future), and an “impact-reducing” strategy (e.g. a strategy enhancing yields by 10% in baseline climate and 20% in the future, and thus mitigating the impact of climate change on yields). Impact-reducing strategies are likely to be the key to resilient and sustainable systems and should therefore receive more attention than strategies whose efficiency decreases with time. However, in this review, the effect of adaptation was quantified as the ratio between yield with and without adaptation in the future, which did not allow us to identify impact-reducing strategies. Our choice was mainly dictated by data availability, as only 36% of selected papers provided a complete dataset including yields with and without adaptation for baseline climate. The few results available sometimes diverged (Figure S12). In particular, irrigated soybeans benefitted less from climate change than rainfed soybeans in several studies (Bao et al., 2015b; Ma et al., 2021; Nendel et al., 2023), while contradictory results were found in others (Marković et al., 2020; Timilsina et al., 2023). This issue needs further investigation in order to avoid overestimating adaptation benefits from some strategies.

Second, the effect of adaptation was generally assessed independently of the technical and economic feasibility of the strategy considered. In particular, 90% of studies assessing the effect of irrigation did not estimate future water availability. It is also uncertain whether virtual genotypes obtained by varying crop traits could realistically be developed in breeding programs. Besides, studies generally overlooked the cost of adaptation. For strategies such as irrigation and increased sowing density, this cost may outweigh the increase in crop productivity (Elliott et al., 2014). Therefore, the evaluation of adaptation strategies would be improved by the development of multi-criteria assessment methodologies including stakeholders’ constraints and objectives (Naulleau et al., 2021, 2022).

4.3. Knowledge gaps and future research avenues

4.3.1. Grain legumes other than soybeans as blind spots

Our review highlighted a need for further European-scale modelling, especially for other grain legumes than soybeans. In agreement with Magrini et al. (2019), we found a great imbalance between soybeans and other grain legumes in the literature, with soybeans representing approximately 80% of selected studies. The paucity of data for these crops contrasts with their prominent positions in European environmental, agricultural, and nutritional policies. We recommend prioritizing research on key species including peas, faba beans, lentils, and chickpeas. To fully comprehend the impact of climate change on these crops, it seems important to differentiate between spring and winter-sown cultivars, as well as rainfed and irrigated crops. However, this differentiation was not consistently made in the papers selected for this review.

Likewise, simulations at the European scale were scarce. Most data on climate change impact originated from global-scale simulations whose coarse resolution masks a wide local heterogeneity (Zhao et al., 2015). Enlarging the study area to climatically similar regions allowed us to compensate for the lack of data in Europe. However, results transferability may be limited by differences in non-climatic parameters such as soil and farm characteristics. Additional work at the European scale seems necessary to support the development of grain legumes, as targeted by European policies.

4.3.2. Choice of the right time and spatial scales

The number of studies assessing the impact of climate change on soybeans in the far future (second part of the XXIst century) contrasted with the paucity of results for the near future. Identifying the timing of risks and key adaptations is necessary to ensure that simulated time periods are not disconnected from stakeholders' needs (Challinor et al., 2018). Therefore, we suggest that farmers and other stakeholders should be included in the process of modelling in order to identify relevant inputs and outputs for future simulations (Naulleau et al., 2022). Stakeholders may also guide an adequate choice of baseline period to avoid misestimating the impact of climate change.

A reflection should also be undertaken on the choice of the spatial scale used in simulations. The effect of some adaptation strategies (e.g. sowing date and cultivar choice) was found site-specific, which points to the need for a local design of adaptation strategies. For other strategies (e.g. shifting to species originating from other agricultural regions, switching grain legume species), effect assessment may be more relevant at the European scale.

The right time and spatial scale will probably depend on the stakeholders. Therefore, multi-scale modelling may be required, as advocated by Peng et al. (2020), who designed a framework from gene to global scale. In the case of grain legumes, we suggest that such a framework should also include crop sequence modelling, as benefits from legumes are strongly dependent on their break-crop effects. Future analyses should also account for the response of cropping mix to climate change. Indeed, the impact of climate change and the effect of adaptation are crop-specific and may lead to changes in crop relative performances and economic profitability. To our knowledge, no study has compared grain legume and cereal response to climate change and adaptation. Further research should explore this issue to investigate whether climate change could enhance or reduce grain legume attractiveness to farmers compared to major crops or innovative minor candidate crops.

4.3.3. A need to broaden the scope of estimated climate change impact

In our analysis, the impact of climate change and the effect of adaptation were mainly quantified in terms of change in yield. However, yield is only one component of the lock-in hindering the development of grain legumes in Europe (Magrini et al., 2016). Other indicators of interest for the stakeholders were found poorly investigated, in particular the impact of climate change on biotic stresses, yield stability, and services provided by grain legumes.

Biotic stresses (weeds, pests, and pathogens) can lead to significant yield losses (Savary et al., 2019) and are likely to be impacted by climate change. Indeed, with the global rise of temperatures, some insects could establish in areas where their proliferation is currently limited by cold temperatures (Bebber et al., 2013; Chaloner et al., 2021). Rising temperatures could also lead to a shortening of reproductive cycles and an increased number of pest generations during crop growing season, thus increasing the influence of pests on yield losses. Elevated CO_2 could increase the relative competitiveness of C3 weeds and make crops less nutritious for insect pests, leading to increased damage (Olesen and Bindi, 2002). In our review, few papers were found on the expected biotic pressure under climate change in Europe, although it is likely that its importance should increase in the future. Most studies used suitability indexes to assess the future overlap between areas suitable to crops and pests, but yield losses were not estimated. Models simulating plant growth and insect life cycles have already been used in other regions of the world to predict future insect damage (Taylor et al., 2018) and could provide valuable information on potential biotic risks and adaptation strategies in Europe.

Farming systems are particularly sensitive to yield shocks (Hristov et al., 2020), and even systems well-adapted to long-term trends will not necessarily be the most resilient against extreme climate events (Rosenzweig and Tubiello, 2007). Therefore, we recommend that projections of future yield variability or risks of crop failure should complement existing data on future average yields. Assessing the impact of climate variability on yields will require improving model calibration and representation of climate extremes and CO_2 effect, especially for minor crops such as grain legumes (Kersebaum, 2022; Rötter et al., 2018). Designing successful strategies to cope with climate variability may also require new approaches. For example, instead of relying on future climate estimates, adaptation strategies could be designed with the aim of being effective under a wide range of climate conditions (Corbeels et al., 2018).

Finally, as grain legumes are often grown for the N-related ecosystem services they provide, we suggest that future simulations should investigate the impact of climate change on N fixation and provision. Non-yield benefits of adaptation strategies should also be assessed, as well as potential interactions between adaptation and climate change mitigation. Given Europe’s growing interest in grain legumes as high-quality protein crops, changes in grain quality and protein content should be simulated to complement already existing experimental data (Scheelbeek et al., 2018).

5. Conclusion

This systematic review provides an original synthesis of model-based studies simulating the impact of climate change and the effect of adaptation on grain legume performances in Europe. Overall, the positive impact of climate change on soybean yields in Northern Europe was relatively consensual among studies, while yield losses may be expected in Southern and Eastern Europe. Although the spatial pattern appeared similar to soybean, lack of data prevented drawing a robust conclusion for other grain legumes at the European scale. Irrigation, changes in sowing date, and cultivar choice were among the most promising adaptation strategies, although authors seldom assessed their environmental desirability and economic feasibility. Alternative soil management generally had a neutral or negative impact on yields but provided secondary benefits, which could motivate its adoption.

The main knowledge gaps identified were a lack of data for other grain legumes than soybeans and a need for more Europe-focused studies, especially for adaptation effect assessment. Modelling the impact of climate change and adaptation remains an open research avenue for key crops such as field peas and faba beans. Only a few studies considered crop response to elevated CO_2, ozone, and biotic pressure. Therefore, incorporating these factors would enhance climate change impact assessment. We also suggest that future simulations should broaden the range of adaptation tested (e.g. intercropping, choice of the grain legume species, combinations of several adaptation strategies) and indicators assessed (e.g. economic indicators, yield variability), in the frame of a multi-criteria analysis.

Altogether, these points highlight a research focus on just a few aspects of climate change and adaptation, leaving in the dark important issues and challenges for stakeholders. Involving stakeholders would help orient future modelling, in order to provide relevant output to inform adaptation, within the scope of a use-oriented approach.

References

Abramoff, R. Z., Ciais, P., Zhu, P., Hasegawa, T., Wakatsuki, H., and Makowski, D. (2023). Adaptation Strategies Strongly Reduce the Future Impacts of Climate Change on Simulated Crop Yields. *Earth's Future*, *11*(4), 1–13. https://doi.org/10.1029/2022EF003190

Ahmed, M., Sameen, A., Parveen, H., Ullah, M. I., Fahad, S., and Hayat, R. (2022). Climate Change Impacts on Legume Crop Production and Adaptation Strategies. In *Global Agricultural Production: Resilience to Climate Change* (pp. 149–181). Springer International Publishing. https://doi.org/10.1007/978-3-031-14973-3_5

Amiri, S., Eyni-Nargeseh, H., Rahimi-Moghaddam, S., and Azizi, K. (2021). Water use efficiency of chickpea agro-ecosystems will be boosted by positive effects of CO2 and using suitable genotype × environment × management under climate change conditions. *Agricultural Water Management*, *252*(April), 106928. https://doi.org/10.1016/j.agwat.2021.106928

Appelhans, T., Detsch, F., Reudenbach, C., and Woellauer, S. (2023). *mapview: Interactive Viewing of Spatial Data in R* (R package version 2.11.0.9006). https://github.com/r-spatial/mapview

Araji, H. A., Wayayok, A., Bavani, A. R. M., Amiri, E., Abdullah, A. F., Daneshian, J., and Teh, C. B. S. (2018). Impacts of climate change on soybean production under different treatments of field experiments considering the uncertainty of general circulation models. *Agricultural Water Management*, *205*(January), 63–71. https://doi.org/10.1016/j.agwat.2018.04.023

Baez-Gonzalez, A. D., Fajardo-Díaz, R., Garcia-Romero, G., Osuna-Ceja, E., Kiniry, J. R., and Meki, M. N. (2020). High Sowing Densities in Rainfed Common Beans (Phaseolus vulgaris L.) in Mexican Semi-Arid Highlands under Future Climate Change. *Agronomy*, *10*(3). https://doi.org/10.3390/agronomy10030442

Bao, Y., Hoogenboom, G., McClendon, R. W., and Paz, J. O. (2015a). Potential adaptation strategies for rainfed soybean production in the south-eastern USA under climate change based on the CSM-CROPGRO-Soybean model. *Journal of Agricultural Science*, *153*(5), 798–824. https://doi.org/10.1017/S0021859614001129

Bao, Y., Hoogenboom, G., McClendon, R. W., and Urich, P. (2015b). Soybean production in

2025 and 2050 in the southeastern USA based on the SimCLIM and the CSM-CROPGRO-Soybean models. *Climate Research*, *63*(1), 73–89. https://doi.org/10.3354/cr01281

Basche, A. D., Archontoulis, S. V., Kaspar, T. C., Jaynes, D. B., Parkin, T. B., and Miguez, F. E. (2016). Simulating long-term impacts of cover crops and climate change on crop production and environmental outcomes in the Midwestern United States. *Agriculture, Ecosystems and Environment*, *218*, 95–106. https://doi.org/10.1016/j.agee.2015.11.011

Battisti, R., Sentelhas, P. C., Boote, K. J., Gil, G. M., Farias, J. R. B., and Basso, C. J. (2017). Assessment of soybean yield with altered water-related genetic improvement traits under climate change in Southern Brazil. *European Journal of Agronomy*, *83*, 1–14. https://doi.org/10.1016/j.eja.2016.11.004

Battisti, R., Sentelhas, P. C., Parker, P. S., Nendel, C., Câmara, G. M. D. S., Farias, J. R. B. B., and Basso, C. J. (2018). Assessment of crop-management strategies to improve soybean resilience to climate change in Southern Brazil. *Crop and Pasture Science*, *69*(2), 154. https://doi.org/10.1071/CP17293

Baule, W., Allred, B., Frankenberger, J., Gamble, D., Andresen, J., Gunn, K. M., and Brown, L. (2017). Northwest Ohio crop yield benefits of water capture and subirrigation based on future climate change projections. *Agricultural Water Management*, *189*, 87–97. https://doi.org/10.1016/j.agwat.2017.04.019

Bebber, D. P., Ramotowski, M. A. T., and Gurr, S. J. (2013). Crop pests and pathogens move polewards in a warming world. *Nature Climate Change*, *3*(11), 985–988. https://doi.org/10.1038/nclimate1990

Bedoussac, L., Journet, E.-P., Hauggaard-Nielsen, H., Naudin, C., Corre-Hellou, G., Jensen, E. S., Prieur, L., and Justes, E. (2015). Ecological principles underlying the increase of productivity achieved by cereal-grain legume intercrops in organic farming. A review. *Agronomy for Sustainable Development*, *35*(3), 911–935. https://doi.org/10.1007/s13593-014-0277-7

Beiranvand, J. P., and Ghamghami, M. (2022). Yield response to climate change and reduced water use: a comparison between parent and nuclear-mutant lines of soybean. *Modeling Earth Systems and Environment*, *8*(4), 5467–5478. https://doi.org/10.1007/s40808-022-01429-z

Bhat, K. A., Mahajan, R., Pakhtoon, M. M., Urwat, U., Bashir, Z., Shah, A. A., Agrawal, A., Bhat, B., Sofi, P. A., Masi, A., and Zargar, S. M. (2022). Low Temperature Stress Tolerance: An Insight Into the Omics Approaches for Legume Crops. *Frontiers in Plant Science*, *13*(June). https://doi.org/10.3389/fpls.2022.888710

Bhattacharya, A. (2010). Physiological responses of grain legumes to stress environments. In *Climate Change and Management of Cool Season Grain Legume Crops* (pp. 35–86). Springer.

Cai, C., Xiao, J., Wan, J., Ren, Z., Van Kleunen, M., and Li, J. (2022). Implications of climate change for environmental niche overlap between five Cuscuta pest species and their two main Leguminosae host crop species. *Weed Science*, *70*(5), 543–552. https://doi.org/10.1017/wsc.2022.45

Carr, T. W., Mkuhlani, S., Segnon, A. C., Ali, Z., Zougmoré, R., Dangour, A. D., Green, R., and Scheelbeek, P. (2022). Climate change impacts and adaptation strategies for crops in West Africa: A systematic review. *Environmental Research Letters*, *17*(5). https://doi.org/10.1088/1748-9326/ac61c8

Cernay, C., Ben-Ari, T., Pelzer, E., Meynard, J.-M., and Makowski, D. (2015). Estimating variability in grain legume yields across Europe and the Americas. *Scientific Reports*, *5*(1), 11171. https://doi.org/10.1038/srep11171

Cernay, C., Makowski, D., and Pelzer, E. (2018). Preceding cultivation of grain legumes increases cereal yields under low nitrogen input conditions. *Environmental Chemistry Letters*, *16*(2), 631–636. https://doi.org/10.1007/s10311-017-0698-z

Challinor, A. J., Müller, C., Asseng, S., Deva, C., Nicklin, K. J., Wallach, D., Vanuytrecht, E., Whitfield, S., Ramirez-Villegas, J., and Koehler, A. K. (2018). Improving the use of crop models for risk assessment and climate change adaptation. *Agricultural Systems*, *159*(June 2017), 296–306. https://doi.org/10.1016/j.agsy.2017.07.010

Challinor, A. J., Watson, J., Lobell, D. B., Howden, S. M., Smith, D. R., and Chhetri, N. (2014). A meta-analysis of crop yield under climate change and adaptation. *Nature Climate Change*, *4*(4), 287–291. https://doi.org/10.1038/nclimate2153

Chaloner, T. M., Gurr, S. J., and Bebber, D. P. (2021). Plant pathogen infection risk tracks global crop yields under climate change. *Nature Climate Change*, *11*(8), 710–715. https://doi.org/10.1038/s41558-021-01104-8

Chen, J., Jiang, K., Wang, S., Li, Y., Zhang, Y., Tang, Z., and Bu, W. (2023). Climate change impacts on the potential worldwide distribution of the soybean pest, Piezodorus guildinii (Hemiptera: Pentatomidae). *Journal of Economic Entomology*, *116*(3), 761–770. https://doi.org/10.1093/jee/toad058

Coleman, K., Whitmore, A. P., Hassall, K. L., Shield, I., Semenov, M. A., Dobermann, A., Bourhis, Y., Eskandary, A., and Milne, A. E. (2021). The potential for soybean to diversify the production of plant-based protein in the UK. *Science of the Total Environment*, *767*, 144903. https://doi.org/10.1016/j.scitotenv.2020.144903

Corbeels, M., Berre, D., Rusinamhodzi, L., and Lopez-Ridaura, S. (2018). Can we use crop modelling for identifying climate change adaptation options? *Agricultural and Forest Meteorology*, *256–257*, 46–52. https://doi.org/10.1016/j.agrformet.2018.02.026

Davis, J., Sonesson, U., Baumgartner, D. U., and Nemecek, T. (2010). Environmental impact of four meals with different protein sources: Case studies in Spain and Sweden. *Food Research International*, *43*(7), 1874–1884. https://doi.org/10.1016/j.foodres.2009.08.017

Deryng, D., Conway, D., Ramankutty, N., Price, J., and Warren, R. (2014). Global crop yield response to extreme heat stress under multiple climate change futures. *Environmental Research Letters*, *9*(3), 034011. https://doi.org/10.1088/1748-9326/9/3/034011

Deryng, D., Sacks, W. J., Barford, C. C., and Ramankutty, N. (2011). Simulating the effects of climate and agricultural management practices on global crop yield. *Global Biogeochemical Cycles*, *25*(2). https://doi.org/10.1029/2009GB003765

Dutta, A., Trivedi, A., Nath, C. P., Gupta, D. Sen, and Hazra, K. K. (2022). A comprehensive review on grain legumes as climate-smart crops: Challenges and prospects. *Environmental Challenges*, *7*, 100479. https://doi.org/https://doi.org/10.1016/j.envc.2022.100479

Elli, E. F., Ciampitti, I. A., Castellano, M. J., Purcell, L. C., Naeve, S., Grassini, P., La Menza, N. C., Moro Rosso, L., de Borja Reis, A. F., Kovács, P., and Archontoulis, S. V. (2022). Climate Change and Management Impacts on Soybean N Fixation, Soil N Mineralization, N2O Emissions, and Seed Yield. *Frontiers in Plant Science*, *13*. https://doi.org/10.3389/fpls.2022.849896

Elliott, J., Deryng, D., Müller, C., Frieler, K., Konzmann, M., Gerten, D., Glotter, M., Flörke, M., Wada, Y., Best, N., Eisner, S., Fekete, B. M., Folberth, C., Foster, I., Gosling, S. N., Haddeland, I., Khabarov, N., Ludwig, F., Masaki, Y., … Wisser, D. (2014). Constraints and potentials of future irrigation water availability on agricultural production under climate change. *Proceedings of the National Academy of Sciences of the United States of America*, *111*(9), 3239–3244. https://doi.org/10.1073/pnas.1222474110

European Commission. (2020). *A Farm to Fork Strategy*. https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52020DC0381

Falconnier, G. N., Vermue, A., Journet, E.-P., Christina, M., Bedoussac, L., and Justes, E. (2020). Contrasted response to climate change of winter and spring grain legumes in southwestern France. *Field Crops Research*, *259*, 107967. https://doi.org/https://doi.org/10.1016/j.fcr.2020.107967

FAOSTAT. (2023). *FAOSTAT database (domains: Crops and livestock products and Land use)*. https://www.fao.org/faostat/en/

Farooq, M., Gogoi, N., Barthakur, S., Baroowa, B., Bharadwaj, N., Alghamdi, S. S., and Siddique, K. H. M. (2017). Drought Stress in Grain Legumes during Reproduction and Grain Filling. *Journal of Agronomy and Crop Science*, *203*(2), 81–102. https://doi.org/10.1111/jac.12169

Farrell, A. D., Deryng, D., and Neufeldt, H. (2023). Modelling adaptation and transformative adaptation in cropping systems: recent advances and future directions. *Current Opinion in Environmental Sustainability*, *61*, 101265. https://doi.org/10.1016/j.cosust.2023.101265

Feng, L., Wang, H., Ma, X., Peng, H., and Shan, J. (2021). Modeling the current land suitability and future dynamics of global soybean cultivation under climate change scenarios. *Field Crops Research*, *263*(January 2020), 108069. https://doi.org/10.1016/j.fcr.2021.108069

Fodor, N., Challinor, A., Droutsas, I., Ramirez-Villegas, J., Zabel, F., Koehler, A.-K., and Foyer, C. H. (2017). Integrating Plant Science and Crop Modeling: Assessment of the Impact of Climate Change on Soybean and Maize Production. *Plant and Cell Physiology*, *58*(11), 1833–1847. https://doi.org/10.1093/pcp/pcx141

Fu, T., Ha, B., and Ko, J. (2016). Simulation of CO2 enrichment and climate change impacts on soybean production. *International Agrophysics*, *30*(1), 25–37. https://doi.org/10.1515/intag-2015-0069

Gogoi, N., Farooq, M., Barthakur, S., Baroowa, B., Paul, S., Bharadwaj, N., and Ramanjulu, S. (2018). Thermal Stress Impacts on Reproductive Development and Grain Yield in Grain Legumes. *Journal of Plant Biology*, *61*(5), 265–291. https://doi.org/10.1007/s12374-018-0130-7

Guilpart, N., Iizumi, T., and Makowski, D. (2022). Data-driven projections suggest large opportunities to improve Europe's soybean self-sufficiency under climate change. *Nature Food*, *3*(4), 255–265. https://doi.org/10.1038/s43016-022-00481-3

Hasegawa, T., Wakatsuki, H., Ju, H., Vyas, S., Nelson, G. C., Farrell, A., Deryng, D., Meza, F., and Makowski, D. (2022). A global dataset for the projected impacts of climate change on four major crops. *Scientific Data*, *9*(1), 58. https://doi.org/10.1038/s41597-022-01150-7

Hatfield, J. L., Boote, K. J., Kimball, B. A., Ziska, L. H., Izaurralde, R. C., Ort, D., Thomson, A. M., and Wolfe, D. (2011). Climate impacts on agriculture: Implications for crop production. *Agronomy Journal*, *103*(2), 351–370. https://doi.org/10.2134/agronj2010.0303

He, Q., Liu, D. L., Wang, B., Li, L., Cowie, A., Simmons, A., Zhou, H., Tian, Q., Li, S., Li, Y., Liu, K., Yan, H., Harrison, M. T., Feng, P., Waters, C., Li, G. D., de Voil, P., and Yu, Q. (2022). Identifying effective agricultural management practices for climate change adaptation and mitigation: A win-win strategy in South-Eastern Australia. *Agricultural Systems*, *203*(April). https://doi.org/10.1016/j.agsy.2022.103527

He, W., Yang, J. Y., Drury, C. F., Smith, W. N., Grant, B. B., He, P., Qian, B., Zhou, W., and Hoogenboom, G. (2018). Estimating the impacts of climate change on crop yields and N2O emissions for conventional and no-tillage in Southwestern Ontario, Canada. *Agricultural Systems*, *159*, 187–198. https://doi.org/10.1016/j.agsy.2017.01.025

Hernangómez, D. (2023). *giscoR: Download Map Data from GISCO API - Eurostat* (0.3.5). https://doi.org/10.5281/zenodo.4317946

Hristov, J., Toreti, A., Pérez Domínguez, I., Dentener, F., Fellmann, T., Elleby, C., Ceglar, A., Fumagalli, D., Niemeyer, S., Cerrani, I., Panarello, L., and Bratu, M. (2020). Analysis of climate change impacts on EU agriculture by 2050. In *Publications Office of the European Union*. https://doi.org/10.2760/121115

Iglesias, A., Quiroga, S., Moneo, M., and Garrote, L. (2012). From climate change impacts to the development of adaptation strategies: Challenges for agriculture in Europe. *Climatic Change*, *112*(1), 143–168. https://doi.org/10.1007/s10584-011-0344-x

Jägermeyr, J., Müller, C., Ruane, A. C., Elliott, J., Balkovic, J., Castillo, O., Faye, B., Foster, I., Folberth, C., Franke, J. A., Fuchs, K., Guarin, J. R., Heinke, J., Hoogenboom, G., Iizumi, T., Jain, A. K., Kelly, D., Khabarov, N., Lange, S., … Rosenzweig, C. (2021). Climate impacts on global agriculture emerge earlier in new generation of climate and crop models. *Nature Food*, *2*(11), 873–885. https://doi.org/10.1038/s43016-021-00400-y

Jancic, M., Lalic, B., Mihailovic, D. T., and Jacimovic, G. (2015). Impact of climate change and carbon dioxide fertilization effect on irrigation water demand and yield of soybean in Serbia. *Journal of Agricultural Science*, *153*(8), 1365–1379. https://doi.org/10.1017/S0021859615000179

Jensen, E. S., and Hauggaard-Nielsen, H. (2003). How can increased use of biological N2 fixation in agriculture benefit the environment? *Plant and Soil*, *252*(1), 177–186. https://doi.org/10.1023/A:1024189029226

Jensen, E. S., Peoples, M. B., Boddey, R. M., Gresshoff, P. M., Hauggaard-Nielsen, H., J.R. Alves, B., and Morrison, M. J. (2012). Legumes for mitigation of climate change and the provision of feedstock for biofuels and biorefineries. A review. *Agronomy for Sustainable Development*, *32*(2), 329–364. https://doi.org/10.1007/s13593-011-0056-7

Jensen, E. S., Peoples, M. B., and Hauggaard-Nielsen, H. (2010). Faba bean in cropping systems. *Field Crops Research*, *115*(3), 203–216. https://doi.org/10.1016/j.fcr.2009.10.008

Jing, Q., Huffman, T., Shang, J., Liu, J., Pattey, E., Morrison, M. J., Jégo, G., and Qian, B. (2017). Modelling soybean yield responses to seeding date under projected climate change scenarios. *Canadian Journal of Plant Science*, *97*(6). https://doi.org/10.1139/CJPS-2017-0065

Kersebaum, K. C. (2022). Modelling to Evaluate Climate Resilience of Crop Rotations Under Climate Change. In C. Kondrup, P. Mercogliano, F. Bosello, J. Mysiak, E. Scoccimarro, A. Rizzo, R. Ebrey, M. DeRuiter, A. Jeuken, & P. Watkiss (Eds.), *CLIMATE ADAPTATION MODELLING* (pp. 87–93). https://doi.org/10.1007/978-3-030-86211-4_11

Knox, J., Daccache, A., Hess, T., and Haro, D. (2016). Meta-analysis of climate impacts and uncertainty on crop yields in Europe. In *Environmental Research Letters* (Vol. 11, Issue

11). IOP Publishing. https://doi.org/10.1088/1748-9326/11/11/113004

Köpke, U., and Nemecek, T. (2010). Ecological services of faba bean. *Field Crops Research*, *115*(3), 217–233. https://doi.org/10.1016/j.fcr.2009.10.012

Kottek, M., Grieser, J., Beck, C., Rudolf, B., and Rubel, F. (2006). World Map of the Köppen-Geiger climate classification updated. *Meteorologische Zeitschrift*, *15*(3), 259–263. https://doi.org/10.1127/0941-2948/2006/0130

Lant, C., Stoebner, T. J., Schoof, J. T., and Crabb, B. (2016). The effect of climate change on rural land cover patterns in the Central United States. *Climatic Change*, *138*(3–4), 585–602. https://doi.org/10.1007/s10584-016-1738-6

Lesk, C., Coffel, E., Winter, J., Ray, D., Zscheischler, J., Seneviratne, S. I., and Horton, R. (2021). Stronger temperature–moisture couplings exacerbate the impact of climate warming on global crop yields. *Nature Food*, *2*(9), 683–691. https://doi.org/10.1038/s43016-021-00341-6

Li, T., Hasegawa, T., Yin, X., Zhu, Y., Boote, K., Adam, M., Bregaglio, S., Buis, S., Confalonieri, R., Fumoto, T., Gaydon, D., Marcaida, M., Nakagawa, H., Oriol, P., Ruane, A. C., Ruget, F., Singh, B., Singh, U., Tang, L., … Bouman, B. (2015). Uncertainties in predicting rice yield by current crop models under a wide range of climatic conditions. *Global Change Biology*, *21*(3), 1328–1341. https://doi.org/10.1111/gcb.12758

Li, Y., Tian, D., Feng, G., Yang, W., and Feng, L. (2021). Climate change and cover crop effects on water use efficiency of a corn-soybean rotation system. *Agricultural Water Management*, *255*(June), 107042. https://doi.org/10.1016/j.agwat.2021.107042

Liu, D. L., Zeleke, K. T., Wang, B., Macadam, I., Scott, F., and Martin, R. J. (2017). Crop residue incorporation can mitigate negative climate change impacts on crop yield and improve water use efficiency in a semiarid environment. *European Journal of Agronomy*, *85*, 51–68. https://doi.org/10.1016/j.eja.2017.02.004

Lobell, D. B. (2014). Climate change adaptation in crop production: Beware of illusions. *Global Food Security*, *3*(2), 72–76. https://doi.org/10.1016/j.gfs.2014.05.002

Lombardozzi, D. L., Bonan, G. B., Levis, S., and Lawrence, D. M. (2018). Changes in Wood Biomass and Crop Yields in Response to Projected CO2, O3, Nitrogen Deposition, and Climate. *Journal of Geophysical Research: Biogeosciences*, *123*(10), 3262–3282. https://doi.org/10.1029/2018JG004680

Lychuk, T. E., Hill, R. L., Izaurralde, R. C., Momen, B., and Thomson, A. M. (2017). Evaluation of climate change impacts and effectiveness of adaptation options on crop yield in the Southeastern United States. *Field Crops Research*, *214*(March), 228–238. https://doi.org/10.1016/j.fcr.2017.09.020

Ma, L., Fang, Q. X., Sima, M. W., Burkey, K. O., and Harmel, R. D. (2021). Simulated climate change effects on soybean production using two crop modules in RZWQM2. *Agronomy Journal*, *113*(2), 1349–1365. https://doi.org/10.1002/agj2.20548

Magrini, M. B., Anton, M., Cholez, C., Corre-Hellou, G., Duc, G., Jeuffroy, M. H., Meynard, J. M., Pelzer, E., Voisin, A. S., and Walrand, S. (2016). Why are grain-legumes rarely present in cropping systems despite their environmental and nutritional benefits? Analyzing lock-in in the French agrifood system. *Ecological Economics*, *126*, 152–162. https://doi.org/10.1016/j.ecolecon.2016.03.024

Magrini, M. B., Cabanac, G., Lascialfari, M., Plumecocq, G., Amiot, M. J., Anton, M., Arvisenet, G., Baranger, A., Bedoussac, L., Chardigny, J. M., Duc, G., Jeuffroy, M. H., Journet, E. P., Juin, H., Larré, C., Leiser, H., Micard, V., Millot, D., Pilet-Nayel, M. L., … Wery, J. (2019). Peer-Reviewed Literature on Grain Legume Species in the WoS (1980–2018): A Comparative Analysis of Soybean and Pulses. *Sustainability (Switzerland)*, *11*(23). https://doi.org/10.3390/su11236833

Makowski, D., Marajo-Petitzon, E., Durand, J. L., and Ben-Ari, T. (2020). Quantitative synthesis of temperature, CO2, rainfall, and adaptation effects on global crop yields. *European Journal of Agronomy*, *115*(May 2019), 126041. https://doi.org/10.1016/j.eja.2020.126041

Malone, R., Garbrecht, J., Busteed, P., Hatfield, J., Todey, D., Gerlitz, J., Fang, Q., Sima, M., Radke, A., Ma, L., Qi, Z., Wu, H., Jaynes, D., and Kaspar, T. (2020). Drainage N loads under climate change with winter rye cover crop in a Northern Mississippi River Basin corn-soybean rotation. *Sustainability (Switzerland)*, *12*(18), 1–18. https://doi.org/10.3390/su12187630

Manners, R., Varela-Ortega, C., and van Etten, J. (2020). Protein-rich legume and pseudo-cereal crop suitability under present and future European climates. *European Journal of Agronomy*, *113*(June 2018), 125974. https://doi.org/10.1016/j.eja.2019.125974

Marchioro, C. A., and Krechemer, F. da S. (2023). Climatic niche shift and distribution of Melanagromyza sojae under current and future climate scenarios: does this species pose a risk to soybean production? *Entomologia Experimentalis et Applicata*, *171*(6), 461–474. https://doi.org/10.1111/eea.13293

Marković, M., Josipović, M., Tovjanin, M. J., Đurđević, V., Ravlić, M., and Barač, Ž. (2020). Validating aquacrop model for rainfed and irrigated maize and soybean production in eastern croatia. *Idojaras*, *124*(2), 277–297. https://doi.org/10.28974/idojaras.2020.2.7

Mihailović, D. T., Lalić, B., Drešković, N., Mimić, G., Djurdjević, V., and Jančić, M. (2015). Climate change effects on crop yields in Serbia and related shifts of Köppen climate zones under the SRES-A1B and SRES-A2. *International Journal of Climatology*, *35*(11), 3320–3334. https://doi.org/10.1002/joc.4209

Minoli, S., Jägermeyr, J., Asseng, S., Urfels, A., and Müller, C. (2022). Global crop yields can be lifted by timely adaptation of growing periods to climate change. *Nature Communications*, *13*(1), 7079. https://doi.org/10.1038/s41467-022-34411-5

Moore, F. C., and Lobell, D. B. (2015). The fingerprint of climate trends on European crop yields. *Proceedings of the National Academy of Sciences*, *112*(9), 2670–2675. https://doi.org/10.1073/pnas.1409606112

Naulleau, A., Gary, C., Prévot, L., Berteloot, V., Fabre, J. C., Crevoisier, D., Gaudin, R., and Hossard, L. (2022). Participatory modeling to assess the impacts of climate change in a Mediterranean vineyard watershed. *Environmental Modelling and Software*, *150*(June 2021). https://doi.org/10.1016/j.envsoft.2022.105342

Naulleau, A., Gary, C., Prévot, L., and Hossard, L. (2021). Evaluating Strategies for Adaptation to Climate Change in Grapevine Production–A Systematic Review. *Frontiers in Plant Science*, *11*. https://doi.org/10.3389/fpls.2020.607859

Nendel, C., Kersebaum, K. C., Mirschel, W., and Wenkel, K. O. (2014). Testing farm management options as climate change adaptation strategies using the MONICA model. *European Journal of Agronomy*, *52*, 47–56. https://doi.org/10.1016/j.eja.2012.09.005

Nendel, C., Reckling, M., Debaeke, P., Schulz, S., Berg-Mohnicke, M., Constantin, J., Fronzek, S., Hoffmann, M., Jakšić, S., Kersebaum, K. C., Klimek-Kopyra, A., Raynal, H., Schoving, C., Stella, T., and Battisti, R. (2023). Future area expansion outweighs increasing drought risk for soybean in Europe. *Global Change Biology*, *29*(5), 1340–1358. https://doi.org/10.1111/gcb.16562

Olesen, J. E., and Bindi, M. (2002). Consequences of climate change for European agricultural productivity, land use and policy. *European Journal of Agronomy*, *16*(4), 239–262. https://doi.org/10.1016/S1161-0301(02)00004-7

Ooms, J. (2023). *magick: Advanced Image-Processing in R*. https://docs.ropensci.org/magick/

Osborne, T., Rose, G., and Wheeler, T. (2013). Variation in the global-scale impacts of climate change on crop productivity due to climate model uncertainty and adaptation. *Agricultural and Forest Meteorology*, *170*, 183–194. https://doi.org/10.1016/j.agrformet.2012.07.006

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., … Moher, D. (2021). The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *BMJ*, n71. https://doi.org/10.1136/bmj.n71

Panagopoulos, Y., Gassman, P. W., Arritt, R. W., Herzmann, D. E., Campbell, T. D., Jha, M. K., Kling, C. L., Srinivasan, R., White, M., and Arnold, J. G. (2014). Surface water quality and cropping systems sustainability under a changing climate in the Upper Mississippi River Basin. *Journal of Soil and Water Conservation*, *69*(6), 483–494. https://doi.org/10.2489/jswc.69.6.483

Panagopoulos, Y., Gassman, P. W., Arritt, R. W., Herzmann, D. E., Campbell, T. D., Valcu, A., Jha, M. K., Kling, C. L., Srinivasan, R., White, M., and Arnold, J. G. (2015). Impacts of climate change on hydrology, water quality and crop productivity in the Ohio-Tennessee River Basin. *International Journal of Agricultural and Biological Engineering*, *8*(3), 1–18. https://doi.org/10.3965/j.ijabe.20150803.1497

Parajuli, P. B., Jayakody, P., Sassenrath, G. F., and Ouyang, Y. (2016). Assessing the impacts of climate change and tillage practices on stream flow, crop and sediment yields from the Mississippi River Basin. *Agricultural Water Management*, *168*, 112–124. https://doi.org/10.1016/j.agwat.2016.02.005

Pasley, H. R., Huber, I., Castellano, M. J., and Archontoulis, S. V. (2020). Modeling Flood-Induced Stress in Soybeans. *Frontiers in Plant Science*, *11*. https://doi.org/10.3389/fpls.2020.00062

Paul, M., Dangol, S., Kholodovsky, V., Sapkota, A. R., Negahban-Azar, M., and Lansing, S. (2020). Modeling the Impacts of Climate Change on Crop Yield and Irrigation in the Monocacy River Watershed, USA. *CLIMATE*, *8*(12). https://doi.org/10.3390/cli8120139

Peltonen-Sainio, P., Jauhiainen, L., Hakala, K., and Ojanen, H. (2009). Climate change and prolongation of growing season: Changes in regional potential for field crop production in Finland. *Agricultural and Food Science*, *18*(3–4), 171–190. https://doi.org/10.2137/145960609790059479

Peng, B., Guan, K., Tang, J., Ainsworth, E. A., Asseng, S., Bernacchi, C. J., Cooper, M., Delucia, E. H., Elliott, J. W., Ewert, F., Grant, R. F., Gustafson, D. I., Hammer, G. L., Jin, Z., Jones, J. W., Kimm, H., Lawrence, D. M., Li, Y., Lombardozzi, D. L., … Zhou, W. (2020). Towards a multiscale crop modelling framework for climate change adaptation assessment. *Nature Plants*, *6*(4), 338–348. https://doi.org/10.1038/s41477-020-0625-3

Peoples, M. B., Hauggaard-Nielsen, H., Huguenin-Elie, O., Jensen, E. S., Justes, E., and Williams, M. (2019). The Contributions of Legumes to Reducing the Environmental Risk of Agricultural Production. In *Agroecosystem Diversity* (pp. 123–143). Elsevier. https://doi.org/10.1016/B978-0-12-811050-8.00008-X

Preissel, S., Reckling, M., Schläfke, N., and Zander, P. (2015). Magnitude and farm-economic value of grain legume pre-crop benefits in Europe: A review. *Field Crops Research*, *175*, 64–79. https://doi.org/10.1016/j.fcr.2015.01.012

Prudhomme, R., Brunelle, T., Dumas, P., Le Moing, A., and Zhang, X. (2020). Assessing the impact of increased legume production in Europe on global agricultural emissions. *Regional Environmental Change*, *20*(3). https://doi.org/10.1007/s10113-020-01651-4

Ramirez-Cabral, N. Y. Z., Kumar, L., and Shabani, F. (2019). Suitable areas of Phakopsora pachyrhizi, Spodoptera exigua, and their host plant Phaseolus vulgaris are projected to reduce and shift due to climate change. *Theoretical and Applied Climatology*, *135*(1–2), 409–424. https://doi.org/10.1007/s00704-018-2385-9

Ramirez-Cabral, N. Y. Z., Kumar, L., and Taylor, S. (2016). Crop niche modeling projects major shifts in common bean growing areas. *Agricultural and Forest Meteorology*, *218–219*, 102–113. https://doi.org/10.1016/j.agrformet.2015.12.002

Ravasi, R. A., Paleari, L., Vesely, F. M., Movedi, E., Thoelke, W., and Confalonieri, R. (2020). Ideotype definition to adapt legumes to climate change: A case study for field pea in Northern Italy. *Agricultural and Forest Meteorology*, *291*(June). https://doi.org/10.1016/j.agrformet.2020.108081

Reckling, M., Döring, T. F., Bergkvist, G., Stoddard, F. L., Watson, C. A., Seddig, S., Chmielewski, F.-M., and Bachinger, J. (2018). Grain legume yields are as stable as other spring crops in long-term experiments across northern Europe. *Agronomy for Sustainable Development*, *38*(6), 63. https://doi.org/10.1007/s13593-018-0541-3

Röös, E., Carlsson, G., Ferawati, F., Hefni, M., Stephan, A., Tidåker, P., and Witthöft, C. (2020). Less meat, more legumes: Prospects and challenges in the transition toward sustainable diets in Sweden. *Renewable Agriculture and Food Systems*, *35*(2), 192–205. https://doi.org/10.1017/S1742170518000443

Rosenzweig, C., Elliott, J., Deryng, D., Ruane, A. C., Müller, C., Arneth, A., Boote, K. J., Folberth, C., Glotter, M., Khabarov, N., Neumann, K., Piontek, F., Pugh, T. A. M., Schmid, E., Stehfest, E., Yang, H., and Jones, J. W. (2014). Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. *Proceedings of the National Academy of Sciences of the United States of America*, *111*(9), 3268–3273. https://doi.org/10.1073/pnas.1222463110

Rosenzweig, C., and Tubiello, F. N. (2007). Adaptation and mitigation strategies in agriculture: An analysis of potential synergies. *Mitigation and Adaptation Strategies for Global Change*, *12*(5), 855–873. https://doi.org/10.1007/s11027-007-9103-8

Rötter, R. P., Appiah, M., Fichtler, E., Kersebaum, K. C., Trnka, M., and Hoffmann, M. P. (2018). Linking modelling and experimentation to better capture crop impacts of agroclimatic extremes—A review. *Field Crops Research*, *221*(March), 142–156. https://doi.org/10.1016/j.fcr.2018.02.023

Ruane, A. C., Antle, J., Elliott, J., Folberth, C., Hoogenboom, G., Mason-D’Croz, D., Müller, C., Porter, C., Phillips, M. M., Raymundo, R. M., Sands, R., Valdivia, R. O., White, J. W., Wiebe, K., and Rosenzweig, C. (2018). Biophysical and economic implications for agriculture of +1.5° and +2.0°C global warming using AgMIP Coordinated Global and Regional Assessments. *Climate Research*, *76*(1), 17–39. https://doi.org/10.3354/cr01520

Rubel, F., Brugger, K., Haslinger, K., and Auer, I. (2017). The climate of the European Alps: Shift of very high resolution Köppen-Geiger climate zones 1800–2100. *Meteorologische Zeitschrift*, *26*(2), 115–125. https://doi.org/10.1127/metz/2016/0816

Salam, M. U., MacLeod, W. J., Salam, K. P., Maling, T., and Barbetti, M. J. (2011). Impact of climate change in relation to ascochyta blight on field pea in Western Australia. *Australasian Plant Pathology*, *40*(4), 397–406. https://doi.org/10.1007/s13313-011-0050-1

Salon, C., Avice, J.-C., Larmure, A., Ourry, A., Prudent, M., and Voisin, A.-S. (2011). Plant N Fluxes and Modulation by Nitrogen, Heat and Water Stresses: A Review Based on Comparison of Legumes and Non Legume Plants. In *Abiotic Stress in Plants - Mechanisms and Adaptations* (Issue June). InTech. https://doi.org/10.5772/23474

Savary, S., Willocquet, L., Pethybridge, S. J., Esker, P., McRoberts, N., and Nelson, A. (2019). The global burden of pathogens and pests on major food crops. *Nature Ecology & Evolution*, *3*(3), 430–439. https://doi.org/10.1038/s41559-018-0793-y

Scheelbeek, P. F. D., Bird, F. A., Tuomisto, H. L., Green, R., Harris, F. B., Joy, E. J. M., Chalabi, Z., Allen, E., Haines, A., and Dangour, A. D. (2018). Effect of environmental changes on vegetable and legume yields and nutritional quality. *Proceedings of the National Academy of Sciences*, *115*(26), 6804–6809. https://doi.org/10.1073/pnas.1800442115

Schneider, A., and Huyghe, C. (2015). Les légumineuses pour des systèmes agricoles et alimentaires durables. In *Les légumineuses pour des systèmes agricoles et alimentaires durables*. éditions Quae. https://doi.org/10.35690/978-2-7592-2335-0

Seifert, C. A., and Lobell, D. B. (2015). Response of double cropping suitability to climate change in the United States. *Environmental Research Letters*, *10*(2). https://doi.org/10.1088/1748-9326/10/2/024002

Smit, B., and Skinner, M. W. (2002). Adaptation options in agriculture to climate change: A typology. *Mitigation and Adaptation Strategies for Global Change*, *7*(1), 85–114. https://doi.org/10.1023/A:1015862228270

Soares, J. R. S., Ramos, R. S., da Silva, R. S., Neves, D. V. C., and Picanço, M. C. (2021). Climate change impact assessment on worldwide rain fed soybean based on species distribution models. *Tropical Ecology*, *62*(4), 612–625. https://doi.org/10.1007/s42965-021-00174-1

Soltani, A., and Sinclair, T. R. (2012). Optimizing chickpea phenology to available water under current and future climates. *European Journal of Agronomy*, *38*(1), 22–31.

https://doi.org/10.1016/j.eja.2011.11.010

Tai, A. P. K., Martin, M. V., and Heald, C. L. (2014). Threat to future global food security from climate change and ozone air pollution. *Nature Climate Change*, *4*(9), 817–821. https://doi.org/10.1038/nclimate2317

Tai, A. P. K., and Val Martin, M. (2017). Impacts of ozone air pollution and temperature extremes on crop yields: Spatial variability, adaptation and implications for future food security. *Atmospheric Environment*, *169*, 11–21. https://doi.org/10.1016/j.atmosenv.2017.09.002

Tatsumi, K., Yamashiki, Y., Valmir da Silva, R., Takara, K., Matsuoka, Y., Takahashi, K., Maruyama, K., and Kawahara, N. (2011). Estimation of potential changes in cereals production under climate change scenarios. *Hydrological Processes*, *25*(17), 2715–2725. https://doi.org/10.1002/hyp.8012

Taylor, R., Herms, D., Cardina, J., and Moore, R. (2018). Climate Change and Pest Management: Unanticipated Consequences of Trophic Dislocation. *Agronomy*, *8*(1), 7. https://doi.org/10.3390/agronomy8010007

Timilsina, A. P., Baigorria, G. A., Wilhite, D., Shulski, M., Heeren, D., Romero, C., and Fensterseifer, C. A. (2023). Soybean response under climatic scenarios with changed mean and variability under rainfed and irrigated conditions in major soybean-growing states of the USA. *The Journal of Agricultural Science*, *161*(2), 157–174. https://doi.org/10.1017/S0021859623000011

Tovjanin, M. J., Djurdjevic, V., Pejic, B., Novkovic, N., Mutavdzic, B., Markovic, M., and Mackic, K. (2019). Modeling the impact of climate change on yield, water requirements, and water use efficiency of maize and soybean grown under moderate continental climate in the pannonian lowland. *Idojaras*, *123*(4), 469–486. https://doi.org/10.28974/idojaras.2019.4.4

Tui, S. H.-K., Descheemaeker, K., Valdivia, R. O., Masikati, P., Sisito, G., Moyo, E. N., Crespo, O., Ruane, A. C., and Rosenzweig, C. (2021). Climate change impacts and adaptation for dryland farming systems in Zimbabwe: a stakeholder-driven integrated multi-model assessment. *Climatic Change*, *168*(1–2), 10. https://doi.org/10.1007/s10584-021-03151-8

Vadez, V., Berger, J. D., Warkentin, T., Asseng, S., Ratnakumar, P., Rao, K. P. C., Gaur, P.

M., Munier-Jolain, N., Larmure, A., Voisin, A.-S., Sharma, H. C., Pande, S., Sharma, M., Krishnamurthy, L., and Zaman, M. A. (2012). Adaptation of grain legumes to climate change: a review. *Agronomy for Sustainable Development*, *32*(1), 31–44. https://doi.org/10.1007/s13593-011-0020-6

van der Schriek, T., Giannakopoulos, C., and Varotsos, K. V. (2020). The impact of future climate change on bean cultivation in the Prespa Lake catchment, northern Greece. *Euro-Mediterranean Journal for Environmental Integration*, *5*(1). https://doi.org/10.1007/s41207-020-0151-8

van Versendaal, E., Carcedo, A. J. P., Adee, E., Sassenrath, G., Dooley, S., Lingenfelser, J., and Ciampitti, I. A. (2023). Integrating Field Data and a Modeling Approach to Inform Optimum Planting Date × Maturity Group for Soybeans under Current and Future Weather Conditions in Kansas. *Sustainability*, *15*(2), 1081. https://doi.org/10.3390/su15021081

Wagner, M., Seidel, S. J., and Schütze, N. (2016). Irrigation water demand of common bean on field and regional scale under varying climatic conditions. *Meteorologische Zeitschrift*, *25*(4), 365–375. https://doi.org/10.1127/metz/2015/0698

Wallach, D., and Thorburn, P. J. (2017). Estimating uncertainty in crop model predictions: Current situation and future prospects. *European Journal of Agronomy*, *88*(September 2016), A1–A7. https://doi.org/10.1016/j.eja.2017.06.001

Wang, B., Liu, D. L., Evans, J. P., Ji, F., Waters, C., Macadam, I., Feng, P., and Beyer, K. (2019). Modelling and evaluating the impacts of climate change on three major crops in south-eastern Australia using regional climate model simulations. *Theoretical and Applied Climatology*, *138*(1–2), 509–526. https://doi.org/10.1007/s00704-019-02843-7

Watson, C. A., Reckling, M., Preissel, S., Bachinger, J., Bergkvist, G., Kuhlman, T., Lindström, K., Nemecek, T., Topp, C. F. E., Vanhatalo, A., Zander, P., Murphy-Bokern, D., and Stoddard, F. L. (2017). Grain Legume Production and Use in European Agricultural Systems. *Advances in Agronomy*, *144*, 235–303. https://doi.org/10.1016/bs.agron.2017.03.003

Weinberg, J., Ota, N., Goergen, G., Fagbohoun, J. R., Tepa-Yotto, G. T., and Kriticos, D. J. (2022). Spodoptera eridania: Current and emerging crop threats from another invasive, pesticide-resistant moth. *Entomologia Generalis*, *42*(5), 701–712. https://doi.org/10.1127/entomologia/2022/1397

White, J. W., Hoogenboom, G., Kimball, B. A., and Wall, G. W. (2011). Methodologies for simulating impacts of climate change on crop production. *Field Crops Research*, *124*(3), 357–368. https://doi.org/10.1016/j.fcr.2011.07.001

Wickham, H. (2016). *ggplot2: Elegant Graphics for Data Analysis*. Springer-Verlag New York. https://ggplot2.tidyverse.org

Zhao, C., Liu, B., Piao, S., Wang, X., Lobell, D. B., Huang, Y., Huang, M., Yao, Y., Bassu, S., Ciais, P., Durand, J.-L., Elliott, J., Ewert, F., Janssens, I. A., Li, T., Lin, E., Liu, Q., Martre, P., Müller, C., … Asseng, S. (2017). Temperature increase reduces global yields of major crops in four independent estimates. *Proceedings of the National Academy of Sciences*, *114*(35), 9326–9331. https://doi.org/10.1073/pnas.1701762114

Zhao, G., Siebert, S., Enders, A., Rezaei, E. E., Yan, C., and Ewert, F. (2015). Demand for multi-scale weather data for regional crop modeling. *Agricultural and Forest Meteorology*, *200*, 156–171. https://doi.org/10.1016/j.agrformet.2014.09.026

Zhao, J., Chen, J., Beillouin, D., Lambers, H., Yang, Y., Smith, P., Zeng, Z., Olesen, J. E., and Zang, H. (2022). Global systematic review with meta-analysis reveals yield advantage of legume-based rotations and its drivers. *Nature Communications*, *13*(1), 4926. https://doi.org/10.1038/s41467-022-32464-0

Zhu, H. (2021). *kableExtra: Construct Complex Table with Kable and Pipe Syntax*. https://github.com/haozhu233/kableExtra

Zhu, X., Troy, T. J., and Devineni, N. (2019). Stochastically modeling the projected impacts of climate change on rainfed and irrigated US crop yields. *Environmental Research Letters*, *14*(7). https://doi.org/10.1088/1748-9326/ab25a1

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Competing interests

The authors declare no competing interests.